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Cooperative Formation Control of Autonomous Underwater Vehicles: An Overview

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Abstract: Formation control is a cooperative control concept in which multiple autonomous underwater mobile robots are deployed for a group motion and/or control mission. This paper presents a brief review on various cooperative search and formation control strategies for multiple autonomous underwater vehicles (AUV) based on literature reported till date. Various cooperative and formation control schemes for collecting huge amount of data based on formation regulation control and formation tracking control are discussed. To address the challenge of detecting AUV failure in the fleet, communication issues, collision and obstacle avoidance are also taken into attention. Stability analysis of the feasible formation is also presented. This paper may be intended to serve as a convenient reference for the further research on formation control of multiple underwater mobile robots.

Keywords: Autonomous underwater vehicles (AUV), cooperative control, formation control, tracking control, regulatory control.

1 Introduction

An autonomous underwater vehicles (AUV) is a submersible underwater vehicle which is equipped with power supply and is controlled by an onboard computer while performing a task. AUVs are compact, independent and low-drag profile crafts powered by underwater direct current(DC) power thrust[1]. AUVs are equipped with sensors to measure temperature, salinity, and pollutant concentration. The underwater vector magnetic fields produced by AUV are as shown in Fig. 1. Motion control of AUVs can be of different types such as based on navigation, path tracking and formation[2]. AUVs are powered by rechargeable batteries (e.g., lithium polymer, nickel metal hydride, lithium ion, aluminum based semi fuel cells, etc.), depending on the length of motion plan. To collect data for mission, various sensors are used for example compasses, depth sensor, side scan sonar, magnetometers, accelerometers, gyro meters, thermistors, doppler velocity log (DVL) and conductivity probes[3].

A number of autonomous underwater vehicles are deployed for a group motion and/or control mission for several important activities such as pipeline inspections in gas and oil industries, oceanographic observations, bathymetric surveys, military usages, recovery of lost man-made objects, high resolution seabed inspection, mapping, commercial survey and neutralization of undersea mines area. To accomplish the cooperative motion successfully, formation control is considered as an important cooperative control paradigm[4].

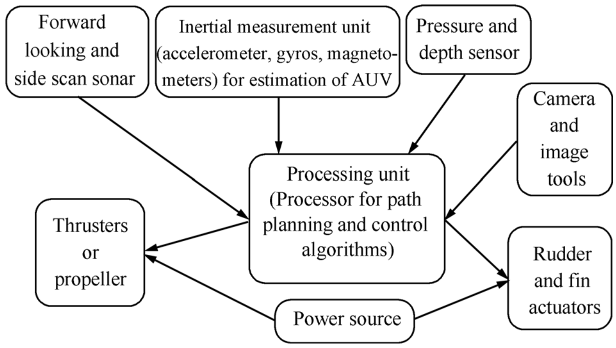

Fig. 1 Simplified block diagram of an AUV architecture[4]

The word autonomous refers to execution of the assigned mission without any external human intercession. AUVs are also known as unmanned undersea vehicles (UUVs) and remotely operated underwater vehicles (ROVs) depending upon their control for the assignment. This means that UUVs are autonomous, whereas non-autonomous remotely operated underwater vehicles controlled and powered from the surface by an operator/pilot are known as ROVs. Based on control structure, AUVs are of two types, fully actuated system and under actuated system[5]. Control laws for a fully-actuated system are developed by using the control allocation map. In an under actuated system, it is challenging to develop a control law together with ensuring the system stability. For both the cases, it is necessary to show the robustness and adaptation of the control structure for the external disturbances. Formation control is an emerging research topic in robotics focusing on controlling the relative positions, velocity and orientations of AUVs to move in a group. It is aimed to accomplish tasks such as mapping, exploration, monitoring of marine environments, data collection for oceanographic missions, security patrols and autonomous navigation information[6]. It increases the

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robustness and efficiency to achieve the task by enhancing the reconfiguration ability and structure flexibility. In military missions, a group of autonomous underwater vehicles are required to keep in a specified formation for area coverage and exploration[7]. In many applications, a group of AUVs are intended to follow a predefined trajectory while maintaining a desired spatial pattern. Due to uncertainty in the AUV dynamics for wave disturbances and communication constraints in the acoustic medium, it is difficult to control AUVs[8, 9].

The idea of formation control comes from nature such as swarming behavior of living beings, flocks of birds, school of fishes, herds of wild beasts and colonies of bacteria[10]. Observing the formation, it is found that when they move as a team, they must avoid colliding with each other and with a common average heading. Each AUV has a local control strategy, to steer towards the average heading of neighbors, steer to avoid crowding and steer towards the average position of neighbor to achieve alignment, separation and cohesion[11]. Underwater mobile robots were used for data gathering and transferring in early 1960. Then around 1970, the first AUV named as Torpedo was developed and used only for test purposes in USA[12]. In mid 1980s, implementation of theoretical developments on AUV were made in the practical fields. Commercialization and development of cooperative motion control of multiple AUVs in both theoretical and practical development are achieved from 1980 till this date as shown in Fig. 2[13].

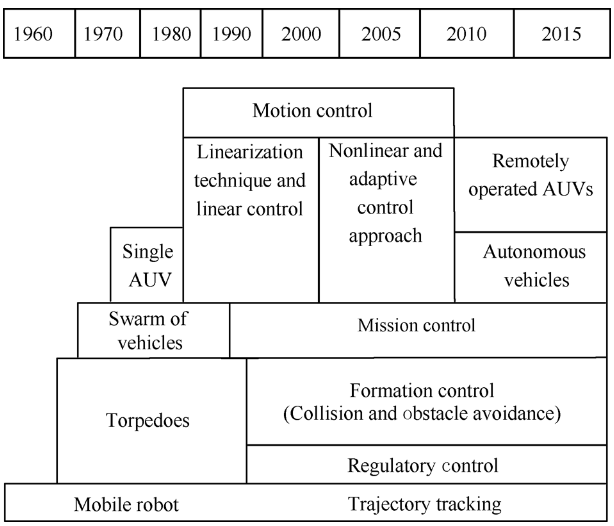


Fig. 2 Studies on formation control of AUVs

A formation control problem considers the following typical aspects: assignment of feasible formation, maintenance of formation shape and switching between formations. Formation control may be classified as formation regulation control and formation tracking control[14]. Formation of a group of AUVs is called a rigid formation where formation structure remains fixed or flexible due to presence of obstacles throughout moving period, which is known as formation regulation control[15]. In order to maintain a group of AUVs in a formation following the desired trajectories, each AUV needs to communicate with its neighbors. This type of formation is known as formation tracking control[16−18]. To achieve a successful formation control of multiple AUVs, the following steps should be followed such as choosing of appropriate AUVs models (both kinematics and dynamics) to stay in formation group, regulatory/trajectory coordination strategies[19−21]. An AUV and/or a group of AUVs in formation or cooperation, play an important role for different applications such as security patrols, search and rescue in hazardous environments[14,17,20]. In military missions, a group of autonomous vehicles is required to keep a specified formation for area coverage and reconnaissance. In small clustering, formation helps to reduce the fuel consumption for propulsion and expand their sensing capabilities. The path following is the method of forcing an AUV along the desired or predefined path without any time constraint. By this method, the AUV starts from an initial point with a definite orientation to reach at the destination point. Sometimes, the controlling of orientation may be avoided according to the necessary degrees of freedom and the directions are controlled by the planner orientations only[16]. In the case of the position controlling problems, the AUVs are directed to merge with the desired positions of the desired path. But in the speed controlling problems, the forward speeds are forced to the desired speeds.

To achieve a successful cooperative control of multiple AUVs, the prerequisite points are chosen by the AUVs to stay in formation group, trajectory[17]. Based on the above, the cooperative control is of two types: 1) formation control of multiple AUVs and 2) flocking control of multiple AUVs. Formation control is an important research topic of the cooperative control within the recent fields of multi-AUV systems[14]. The formation control is referred as the problems of controlling the relative positions and orientations of AUVs in a group while allowing the group to move as a whole as shown in Fig. 3. Formation control consists of the following steps: 1) assignment of feasible formation, 2) maintenance of formation shape to move in formation, 3) switching between formations.

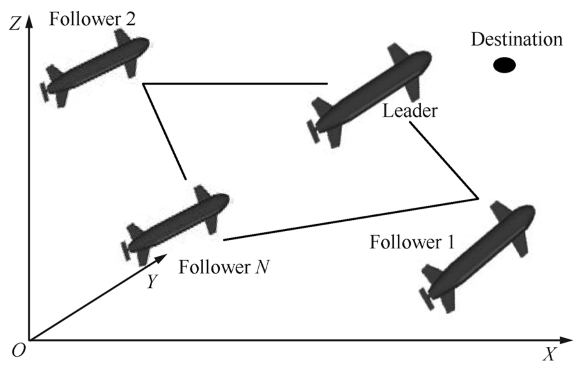


Fig. 3 Formation control of multiple AUVs

Flocking is the flying behavior of a flock of birds, which is a collective behavior of living beings such as schooling of fishes, flocks of birds, grouping of insects, colonies of bacteria and herds of animals, etc. This can be applicable to design control algorithm for a group of multiple AUVs to perform a desired task as shown in Fig. 4. Flocking control of multiple AUVs is similar to that of formation control with the only difference is that there are no constraints on distance among AUVs[18−20]. In case of formation control, the distances among AUVs are always fixed. Our research work only focuses on formation control of multiple AUVs[21].

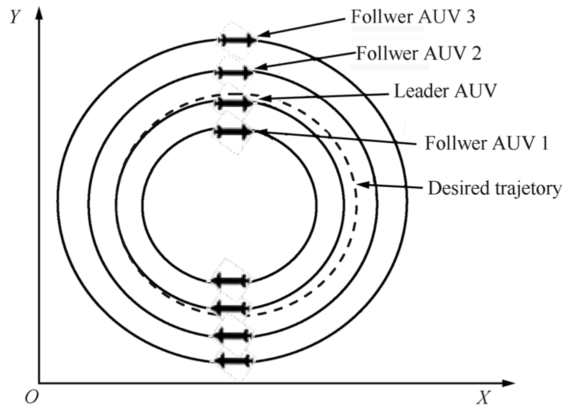


Fig. 4 Flocking control of multiple AUVs

Cooperative control may be classified as formation control and flocking control. The path following is the method of forcing the AUV along the desired predefined path without any time constraint. Flocking control may be achieved by a group of multiple AUVs to perform a desired task. Formation control has broad applications and so it is recognized to occupy the seat of an active research topic in the recent years. The steps for achieving formation control are: 1) assignment of feasible formation, 2) moving in formation, 3) maintenance of formation shape, 4) switching between formations. The definition of formation is specified in three different ways. The ways may be meant to achieve the rigid formation[10], or to achieve a flexible formation in plane[22]. In formation control, it is assumed that information is available for each AUV through local sensors within the formation. In the case of trajectory tracking problems, the follower AUVs are forced to merge a time parameterized geometric path. The control law is designed according to the temporal variations of the desired geometric path[22]. The degree of difficulty of designing control law for formation of underactuated vehicles is very high. The trajectory tracking approach provides better performance for carrying control information on time as compared to the other path formation problem. In the virtual structure approach, the entire formation is treated as a single entity. Control methods are developed to force a group of AUVs to behave in a rigid formation. In virtual structure approach, the control law is derived in three steps[23]. Also the convergence of the AUV to be in formation takes less time than that of the trajectory tracking problem.

The basic principle of behavior based approach is that, each AUV consists of a basic structure called motor schemas[24]. The motor schemas generate their corresponding desired behavior. Some of the motor schemas are collision avoidance, formation shape and goal seeking. In formation control, the behavior-based approach and potential field approach are considered for various applications[25−27]. The control input for the AUV is generated by adjusting using optimization technique. In [23], the virtual structure method is combined with the leader following method and behavioral approach to formation control. In this method, independent paths are derived from the desired path for each AUV[28]. The methodology behind this method requires that the coordination must be achieved for AUVs following their respective desired paths[29, 30]. In other words, it can be said that there exists a velocity and acceleration constraint for each derived path[31].

Only a few papers are available in this field that includes discussions on formation control until 2014. Depending upon the above criteria, the contributions of this paper are as follows. Extensive reviews on formation control of multiple AUVs are listed in this paper. The objectives of this paper are as follows.

1) A detailed description about the system model of AUV in six degree of freedom (DOF) of earth fixed frame is discussed.

2) A peer review on formation control of multiple AUVs based on regulatory and tracking control techniques are briefly explained and stability analysis is also presented[32−37].

3) Various challenges and applications of formation control are also discussed.

This paper is organized as follows. Section 2 describes the kinematics and dynamics of the AUV. Section 3 gives the problem formulation. A detailed description about coordination strategies for formation control is described in Section 4. Section 5 explains various challenges and formation failure issues. Section 6 describes the stability analysis of formation control. Section 7 discusses the various applications of formation control. Section 8 presents the conclusion of this paper.

2 AUV dynamics

Consider the schematic diagram of an AUV as shown in Fig. 5. The mathematical model (nonlinear equation of motion) of identical AUVs under the influence of wave

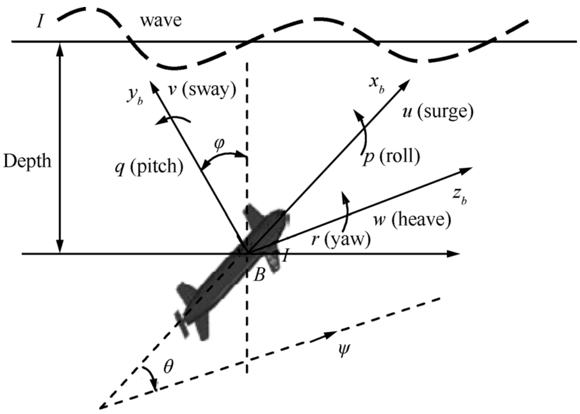


Fig. 5 Inertial and body fixed frames of an AUV model[1]

disturbances in six degrees of freedom can be described as [1, 18 – 20].

$$\dot{\eta}_{1i} = J_1(\eta_{2i})\nu_{1i} \tag{1}$$

$$\dot{\eta}_{2i} = J_1(\eta_{2i})\nu_{2i}. \tag{2}$$

For multiple AUVs, $i = 1,\ 2,\ 3, \cdots, N$, $\eta_i = [\eta_{1i}, \eta_{2i}]^{\rm T}$ is the position and orientation vector of i-th AUV in inertial frame, $\eta_{1i} = [x_i, y_i, z_i]^{\rm T}$ are the coordinates of positions and $\eta_{2i} = [\varphi_i, \theta_i, \psi_i]^{\rm T}$ is orientation along longitudinal, transversal, and vertical axes, respectively. $v_i = [v_{1i}, v_{2i}]^{\rm T}$ is the velocity vector with coordinates in the body-fixed frame, $v_{1i} = [u_i, v_i, w_i]^{\rm T}$ denotes linear velocities, $v_{2i} = [p_i, q_i, r_i]^{\rm T}$ are the angular velocities[1].

$$\dot{\nu}_{1i} = M_1^{-1}(-C_{1i}(\nu_{1i})v_{2i} - D_{1i}(\nu_{1i})v_{1i} - g_1(\eta_{2i}) + \tau_{1i}) \tag{3}$$

$$\dot{\nu}_{2i} = M_2^{-1}(-C_{1i}(\nu_{1i})v_{1i} - C_{2i}(\nu_{2i})v_{2i} - D_{2i}(\nu_{2i})v_{2i} - g_2(\eta_{2i}) + \tau_{2i}) \tag{4}$$

$\tau_i = [\tau_{1i}, \tau_{2i}]^{\rm T}$ is the control input to the i-th AUV, $\tau_{1i} = [X_i, Y_i, Z_i]^{\rm T}$ represents the external forces and $\tau_{2i} = [K_i, M_i, N_i]^{\rm T}$ denotes moments of external forces acting on the AUV for translational and rotational motion respectively. $J(\eta)$ is the non-singular transformation matrix, used for transformation from body fixed frame to earth fixed frame[1]. The inertia mass matrices of AUV are given by

$$M_1 = {\rm diag}(m_{11}, m_{22}, m_{33}) \tag{5}$$
$$M_2 = {\rm diag}(m_{44}, m_{55}, m_{66}). \tag{6}$$

The Coriolis and centripetal matrices are given by[1]

$$C_{1i}(\nu_{1i}) = \begin{bmatrix} 0 & m_{33}w & -m_{22}v \\ -m_{33}w & 0 & m_{11}u \\ m_{22}v & -m_{11}u & 0 \end{bmatrix} \tag{7}$$

$$C_{2i}(\nu_{2i}) = \begin{bmatrix} 0 & m_{66}r & -m_{55}q \\ -m_{66}r & 0 & m_{44}p \\ m_{55}q & -m_{44}p & 0 \end{bmatrix}. \tag{8}$$

The damping matrices including the added mass matrix are[1]

$$D_1(\nu_1) = {\rm diag}(d_{11} + \sum_{i=2}^{3} d_{ui}\,|u|^{i-1}, d_{22} + \sum_{i=2}^{3} d_{vi}\,|v|^{i-1}, d_{33} + \sum_{i=2}^{3} d_{wi}\,|w|^{i-1}) \tag{9}$$

$$D_2(\nu_2) = {\rm diag}(d_{44} + \sum_{i=2}^{3} d_{pi}\,|p|^{i-1}, d_{55} + \sum_{i=2}^{3} d_{qi}\,|q|^{i-1}, d_{66} + \sum_{i=2}^{3} d_{ri}\,|r|^{i-1}). \tag{10}$$

The restoring force and moment vector are given by[1]

$$g_2(\eta_{2i}) = \Big[(W - B)s\theta, -(W - B)c\theta s\varphi, -(W - B)c\theta c\varphi\Big]^{\rm T} \tag{11}$$

$$g_2(\eta_{2i}) = \begin{bmatrix} -(y_GW - y_BB)c\theta c\varphi + (z_GW - z_BB)c\theta s\varphi \\ (z_GW - z_BB)s\theta + (x_GW - x_BB)c\theta c\varphi \\ -(x_GW - x_BB)c\theta s\varphi - (y_GW - y_BB)s\theta \end{bmatrix}^{\rm T} \tag{12}$$

where W is the submerged weight and B is the buoyancy force of each identical AUV[1]. $r_G = [x_G,\ y_G,\ z_G]^{\rm T}$ is the distance between center of gravity of AUV and the origin of the body fixed frame and $r_B = [x_B,\ y_B,\ z_B]^{\rm T}$ is the distance between center of buoyancy of AUV and the origin of the body fixed frame. The rotation matrix of the AUV can be expressed as[1]

$$J_1(\eta_{2i}) = \begin{bmatrix} c\psi_i c\theta_i & -s\psi_i c\theta_i + s\phi_i s\theta_i c\psi_i & s\psi_i s\phi_i + s\theta_i c\psi_i c\phi_i \\ s\psi_i c\theta_i & c\psi_i c\phi_i + s\phi_i s\theta_i s\psi_i & -c\psi_i s\phi_i + s\theta_i s\psi_i c\phi_i \\ -s\theta_i & s\phi_i c\theta_i & c\phi_i c\theta_i \end{bmatrix} \tag{13}$$

$$J_2(\eta_{2i}) = \begin{bmatrix} 1 & s\phi_i t\theta_i & c\phi_i t\theta_i \\ 0 & c\phi_i & -s\phi_i \\ 0 & s\phi_i/c\theta_i & c\phi_i/c\theta_i \end{bmatrix}. \tag{14}$$

3 Problem statement

Control coordination issue relates to the study of the position, path planning and coordination within a defined communication topology in space and time respectively. It is assumed that the common velocity and position signals must be available to all the AUVs with the help of high level sensors. In addition to the above, underwater acoustic channels are affected by the long propagation delay of the acoustic signal, path loss, noise, multipath fading, Doppler spread, and high error probability. Various control

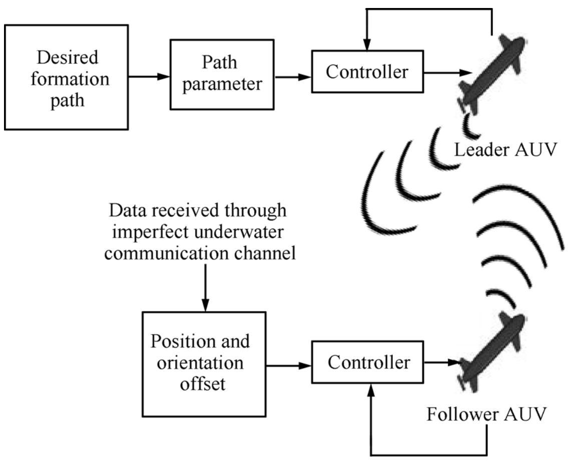


Fig. 6 Control signal flow for formation control of leader-follower AUV

strategies are discussed which enable the follower AUVs to follow the leader as shown in Fig. 6. The formation control referred as the problems of controlling the relative positions and orientations of robots in a group while allowing the group to move as a whole. The information of the desired path of the leader AUV should be known to the follower AUVs to follow the leader with respect to position and orientation. In unreliable underwater network scenarios, it is very challenging to provide full observation communication protocol with energy-efficient reliable data transfer for time critical applications such as coordination. The factors affecting formation control are: 1) assignment of feasible formation control strategies, 2) moving in formation in presence of obstacle rich environment, 3) maintenance of formation shape availing full observation communication, 4) switching between formations.

4 Classification of formation control of AUVs

Generally, formation of AUVs may be categorized as path planning, path following and path tracking[7, 19, 38]. The formation control of AUVs may be static or dynamic depending upon some regulation, whereas, reaching at the target point, the formation structure travels through a particular path known as formation tracking control. According to the above classification, some formation control techniques are enumerated till date as shown in the Fig. 7.

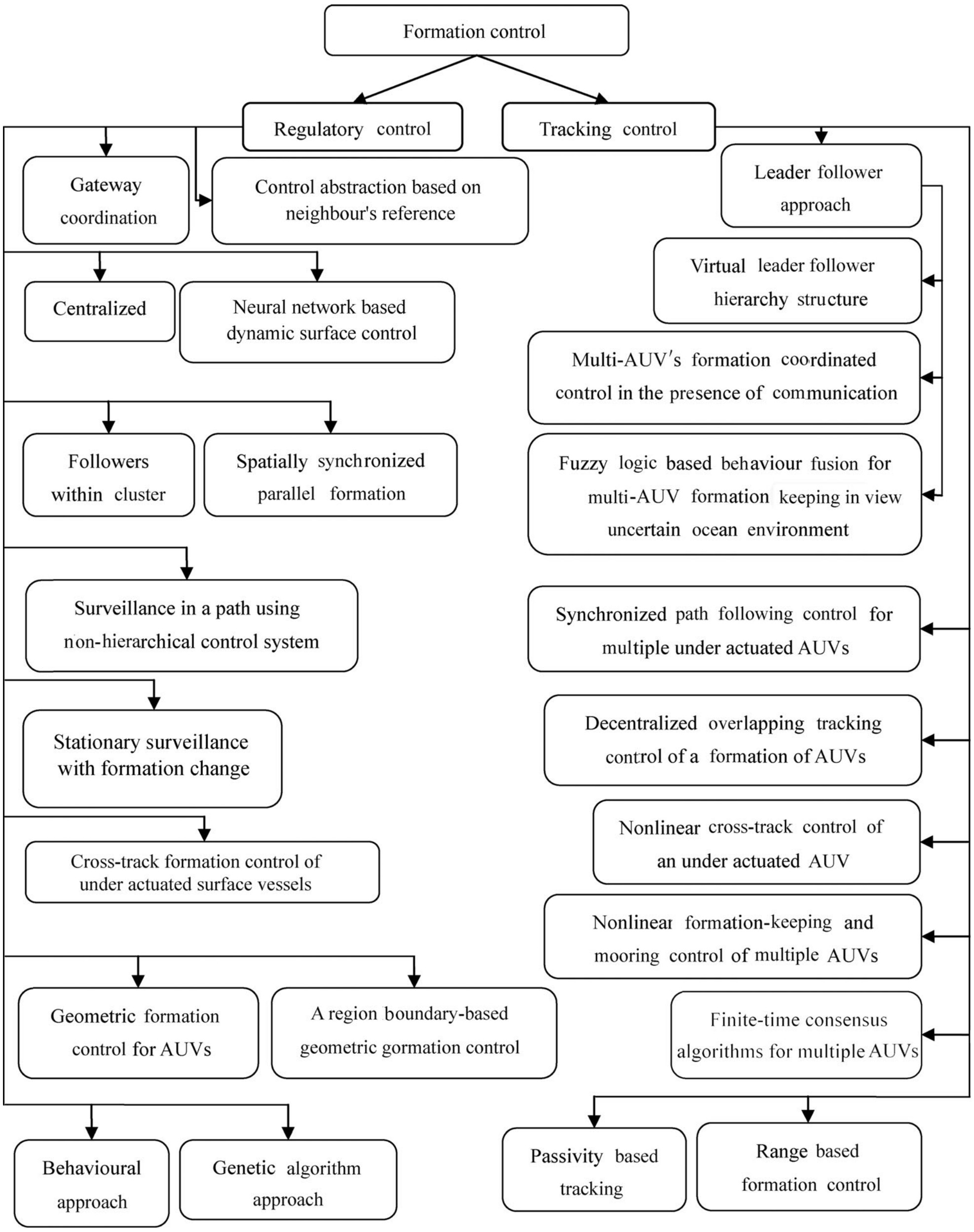


Fig. 7 Classification of formation control of multiple AUVs

The following techniques are some of the widely used formation control applied on underwater systems such as mapping, exploration, monitoring of marine environments, data collection for oceanographic missions and harbour security, etc[39, 40]. For both the cases, such as formation regulation control and tracking control, it is necessary to show the robustness and adaptation of the control structure as shown in Fig. 8.

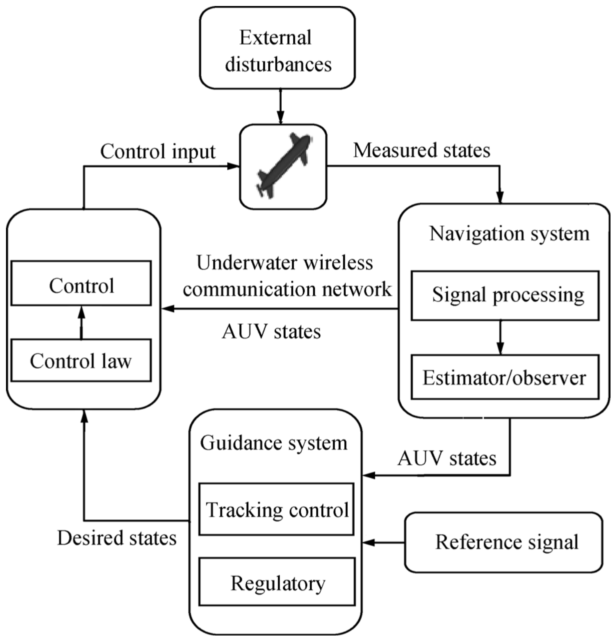


Fig. 8 Studies on formation control of AUVs

4.1 Formation regulation control

A specific shape needs to be maintained in a formation[39]. It is essential to know the control issues based on regulatory control when multiple AUVs are in a cooperative motion. The different techniques for control regulation are presented below and a comparison study is made on various regulatory based formation control strategies as provided in Table 1.

4.1.1 Gateway coordination

In this configuration, an AUV serves as a gateway. Each of the AUV sends its information to gateway and receives the gateway′s position. Coordination is thus achieved through the gateway AUV as shown in Fig. 9[40]. The numbers represent the name of the AUVs, and the arrows present the coordination between the AUVs with their references.

4.1.2 Control abstraction based on neighbor′s reference

An AUV needs to keep a proper position with respect to the position of neighbor AUVs to maintain formation. In Fig. 10, the coordination between the AUVs is shown with their neighbor′s reference such as predecessor, leader and neighbor reference types[13].

According to Wang et al.[40], each AUV communicates to its immediate neighbors for coordination[40] as shown in Fig. 11.

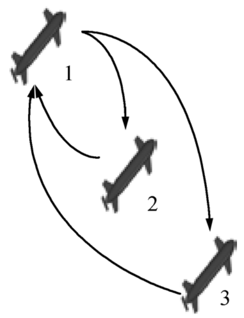


Fig. 9 Gateway coordination of multiple AUVs[13]

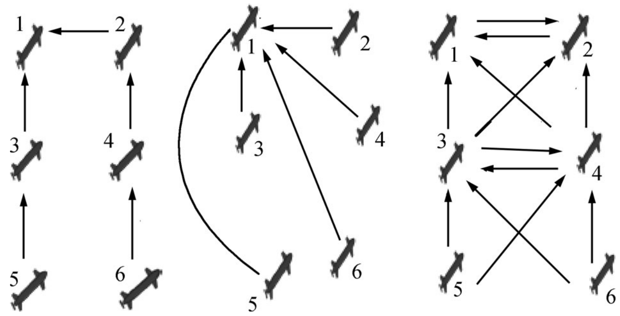


Fig. 10 Different neighbor reference types[40]

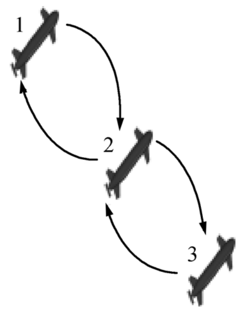


Fig. 11 Spatial pattern of a group of three AUVs, an AUV with the preceding and succeeding AUVs

The n AUVs are indexed according to the spatial pattern they are required to achieve and communicate with the preceding and succeeding AUVs. Different control laws have been reported for the formation control of AUVs such as

1) cooperative control laws applicable to under actuated AUVs with a stationary formation is presented in [41]. 2) Robustness of the cooperative control laws is discussed with communication delays in [41].

Along with the group of AUVs coming into the stationary geometric pattern, each AUV is also required to converge to the same constant orientation as shown in Figs. 12 and 13.

4.1.3 Centralized approach

Here we consider the formation control of multiple AUVs according to a stationary geometric pattern under different communication scenarios. Centralized cooperative control laws are proposed with the aid of suitable transformations and the results on the graph theory as shown in Fig. 14[39]. An efficient formation control for the cooperative motion of

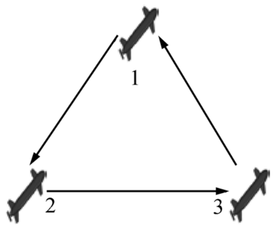


Fig. 12 Spatial pattern of three AUVs using communication digraph

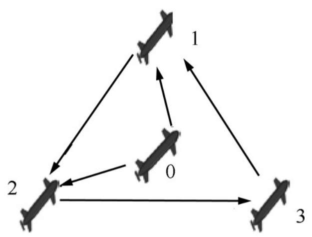


Fig. 13 Spatial pattern of AUVs with virtual agent using communication digraph

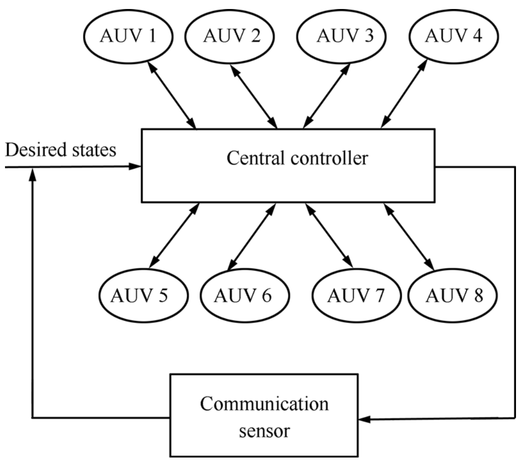


Fig. 14 Coordination of AUVs through a centralized approach[39]

AUVs based on kinematic algorithm for the joint motion of an AUV with a leader AUV has been proposed in [42].

4.1.4 Neural network (NN) based dynamic surface control

Several formation control algorithms rely on the velocity and moment information of leader AUV. However, all AUVs are not equipped with velocity sensors. A NN based formation controller using back propagation learning algorithm eliminates the tracking errors of AUVs whose dynamics are highly nonlinear and time varying[43]. It has good capability to incorporate the dynamics of the system. The proposed NN architectures have been designed to control the test bed for AUV named as naval postgraduate school(NPS) AUV.

4.1.5 Followers within a cluster

A leader-follower based on real-time communication design is adopted for the formation controller. Cluster space state method may be used for achieving formation control of underwater mobile robots as shown in Fig. 15[44].

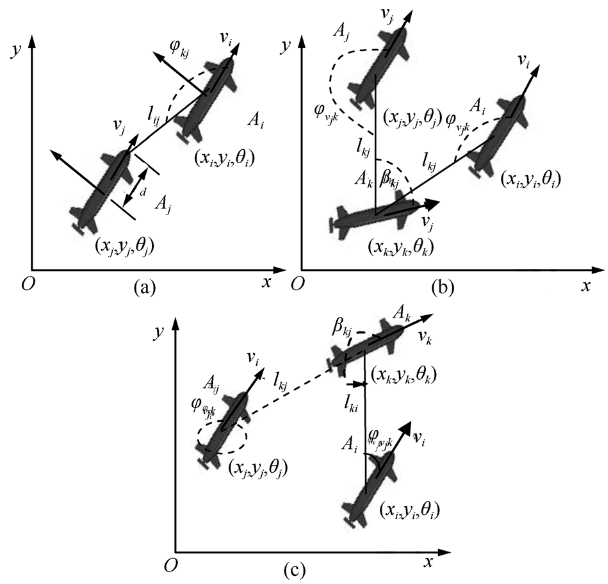


Fig. 15 Cluster based formation control, (a) linear, (b) triangular, (c) inverted triangle[44]

In this method, the whole team of AUVs is divided into different clusters of limited sizes. A local controller is first designed for each cluster, and then formation control is developed by using centralized method[45]. The implementation process of the leader-follower formation control algorithms are discussed such as line-shape, triangle-shape and inverted triangle-shape.

4.1.6 Spatially synchronized parallel formation

A synchronized parallel formation for a fleet of AUVs is developed in [46] which are based on its velocity matching and virtual leader control design. The spatial synchronized parallel formation is the basis of AUVs group′s cooperative control, and is important for group cooperative behaviors, such as formation keeping in the space, communication distance fixing, and observation synchronization as shown in Fig. 16[47].

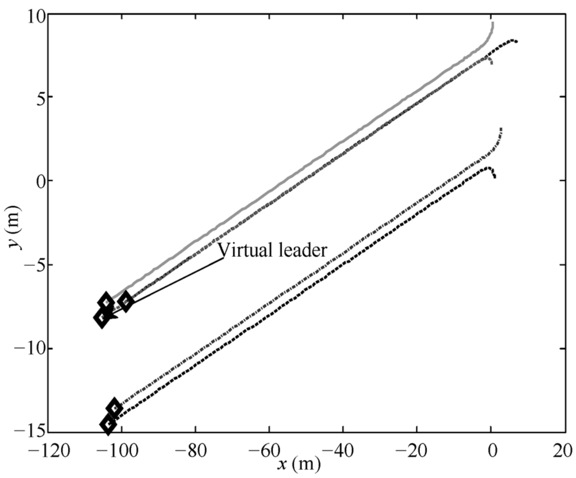


Fig. 16 Spatially synchronized parallel formation

4.1.7 Surveillance on a path using non-hierarchical control system

In the formation control literature, two different types of formation control structures are used based on distribution of control tasks among agents. These are hierarchical and non-hierarchical structures[48]. For a non-hierarchical structure, the distance maintaining and path tracking tasks are uniformly distributed across the formation, i.e., the control tasks distributed to the agents are relatively identical.

Stable periodic formation control of multiple non-holonomic vehicles may be achieved by arranging the vehicles in a cyclic interconnection topology known as "cyclic pursuit"[49]. This cyclic pursuit could be a circular formation either with a fixed[50] or varying radius[51].

4.1.8 Stationary surveillance with formation change

In this formation, the shape maintained by the group of AUVs is rigid throughout. It is necessary to change or to split the shape of the formation if any static or dynamic obstacles come across. Static and dynamic obstacles are given by strong currents, land areas or heavy traffic shipping routes. For example, formation shape may be switched from straight line to wedge shape for stationary surveillance[52] or may be changed from double platoon to other shape[53]. By using the phase waves and phase gradient method the shape of the formation structure can be adapted in a similar fashion as an amoeba in drastic environmental condition. The shape of the formation can be changed and adapted to avoid obstacles by manipulating the potential functions associated with this as shown in Fig. 17[54].

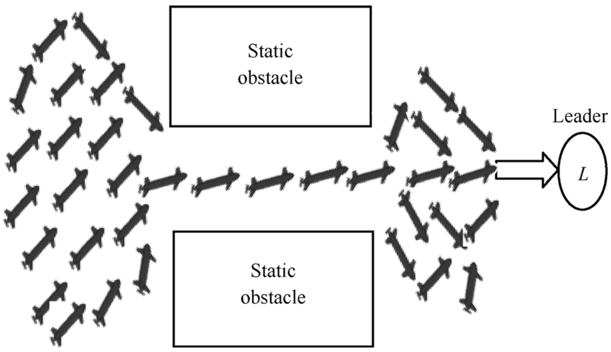


Fig. 17 A group of AUVs change their formation shape to pass through a narrow region

4.1.9 Cross-track formation control

The sliding mode controller proposed by Defoort et al. enables the AUVs to track the desired path at constant speed[55]. Steps followed in [55] to track the desired path are as follows:

1) The first step is based on a line of sight guidance law as in [56, 57], which makes every AUV asymptotically follow a straight line path corresponding to the desired formation motion as shown in Fig. 18. Line of sight range can be estimated by visual sensors. In this range, each AUV can measure its speed and heading angle with respect to other AUVs.

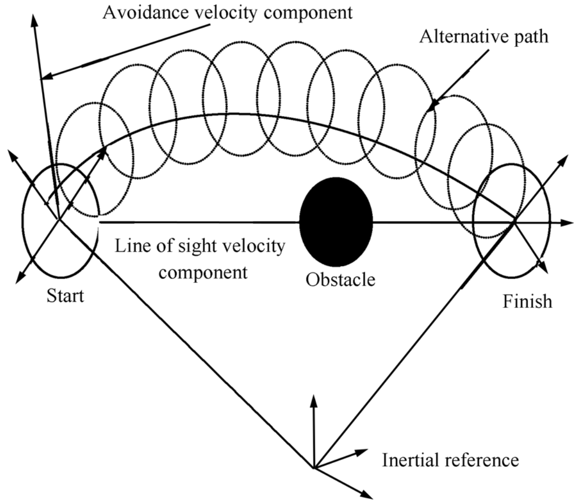


Fig. 18 Line-of-sight and collision-avoidance path components

2) In the second step, the forward speed of every AUV is manipulated in such a way that they asymptotically converge to the desired formation and move with a desired forward speed profile as shown in Fig. 19.

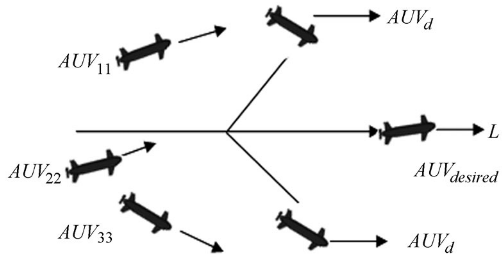


Fig. 19 Group of AUVs change their formation shape to pass through a narrow region

4.1.10 Geometric formation control for AUVs

A group of AUVs may be allocated to reach at the destination through geometrical formation without any collision[58−65]. Geometric formation control of multiple AUVs may be possible by utilizing the Jacobi shape theory as shown in Fig. 20[19, 49, 66], velocity optimization technique[67, 68] and path following control of single AUV are presented in [8, 69−72]. To solve the coordinated path following problem, a hybrid controller is to be developed as shown in Fig. 21[73, 74].

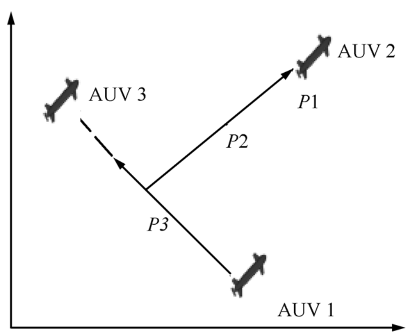


Fig. 20 Jacobi vectors for three AUVs

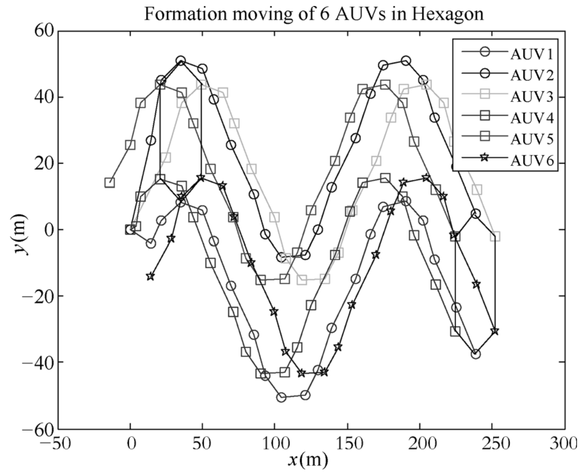


Fig. 21 Six AUVs moving in hexagonal geometrical formation[46]

4.1.11 A region/boundary-based geometric formation control (or asset protection) scheme

The boundary based geometric path following problem of multiple AUVs can be developed for inspection as in [73–75]. In [76], a simple control approach based on a region boundary technique for geometric formation of multiple AUVs is presented.

The control objective is to keep each underwater vehicle at each corner of a desired geometric shape, i.e., an equilateral triangle or a square. An edge-based segmentation approach is utilized rather than specifying the minimum distance between members to ensure that each AUV is placed exactly at the desired position in their formation[63, 77]. This allows each vehicle that has its own function to carry out an effective individual task[78, 79], thus improving the formation performance as shown in Fig. 22.

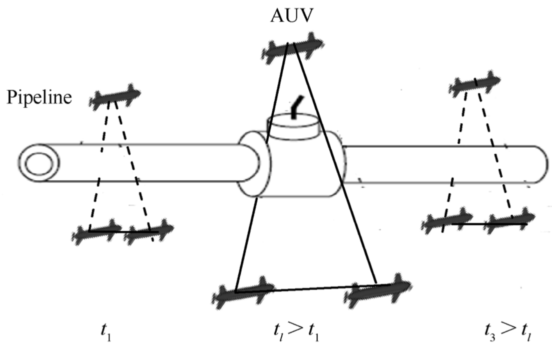


Fig. 22 An illustration of task for AUVs

4.1.12 Behavioural approach of formation

The behavioral approach starts from behavior of individual AUV as shown in Fig. 23[80]. The common behaviors are goal seeking, obstacle avoidance, keeping the consistent formation, etc.

Therefore, more complex motion pattern can be generated by using the individual behavior of separate AUVs. The architecture of behavior based formation control of a team of AUVs consists of three levels, i.e., team behavior or team formation pattern, AUV task and behavior, and AUV control[81, 82].

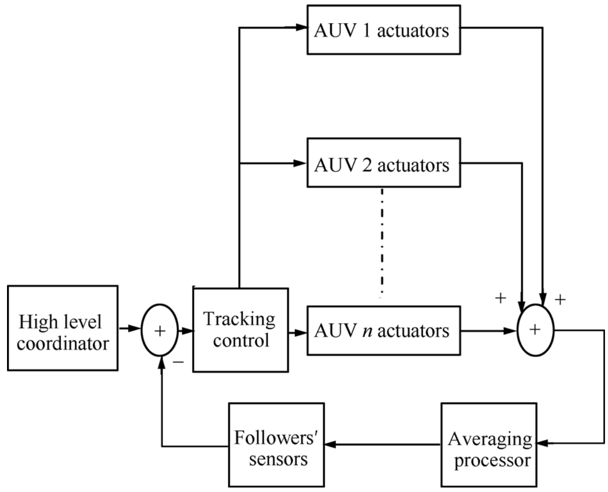


Fig. 23 Control structure of formation control of multiple vehicles via behavior-based approach and potential field approach[80]

4.2 Formation tracking control

4.2.1 Leader-follower approach

In this formation tracking control technique, an AUV is elected as the leader AUV, executes a path following algorithm at a required forward speed and relays its position to the remaining AUVs[40, 83]. It is up to the followers to keep the formation, based on information received from the leader as shown in Fig. 24.

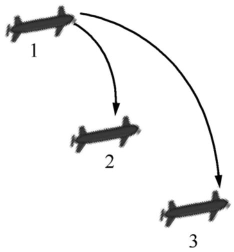


Fig. 24 An illustration of task for AUVs

4.2.2 Virtual leader-follower hierarchy structure

The dynamic behavior of leader represents the whole cluster behavior. If the leader behavior within a certain period is predefined, other AUVs within the cluster just obey the leader to track the leader′s trajectory as shown in Fig. 25[84, 85].

4.2.3 Formation coordinated control in the presence of communication losses

This paper addresses the problem of steering a group of AUVs along the given paths while holding a desired inter-vehicle formation pattern, all in the presence of communication losses as shown in Fig. 26[67]. The dynamics of each autonomous underwater vehicle can be dealt with each AUV controller locally. Coordination can then be achieved by resorting to a decentralized control law whereby the exchange of data among the vehicles is kept at a minimum.

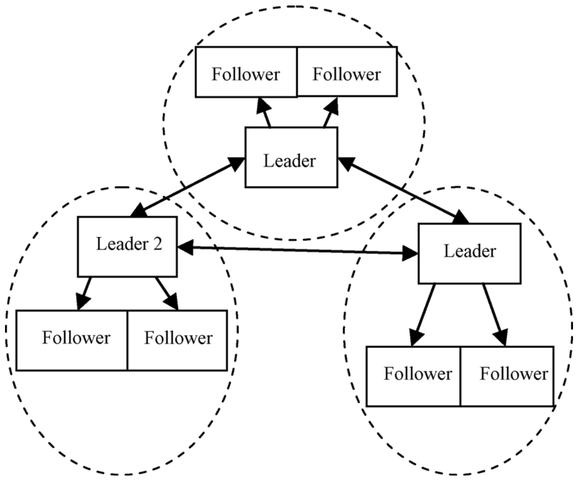


Fig. 25 An illustration of task for AUVs

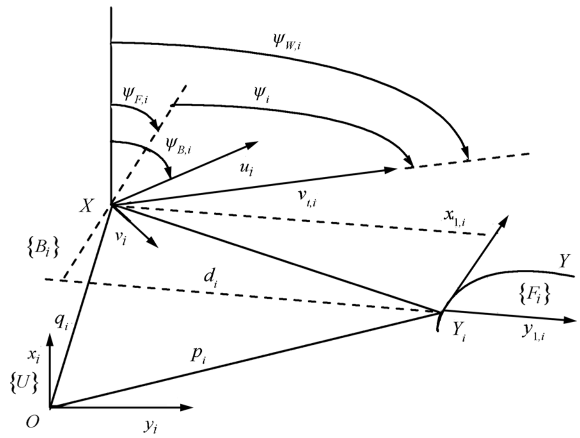


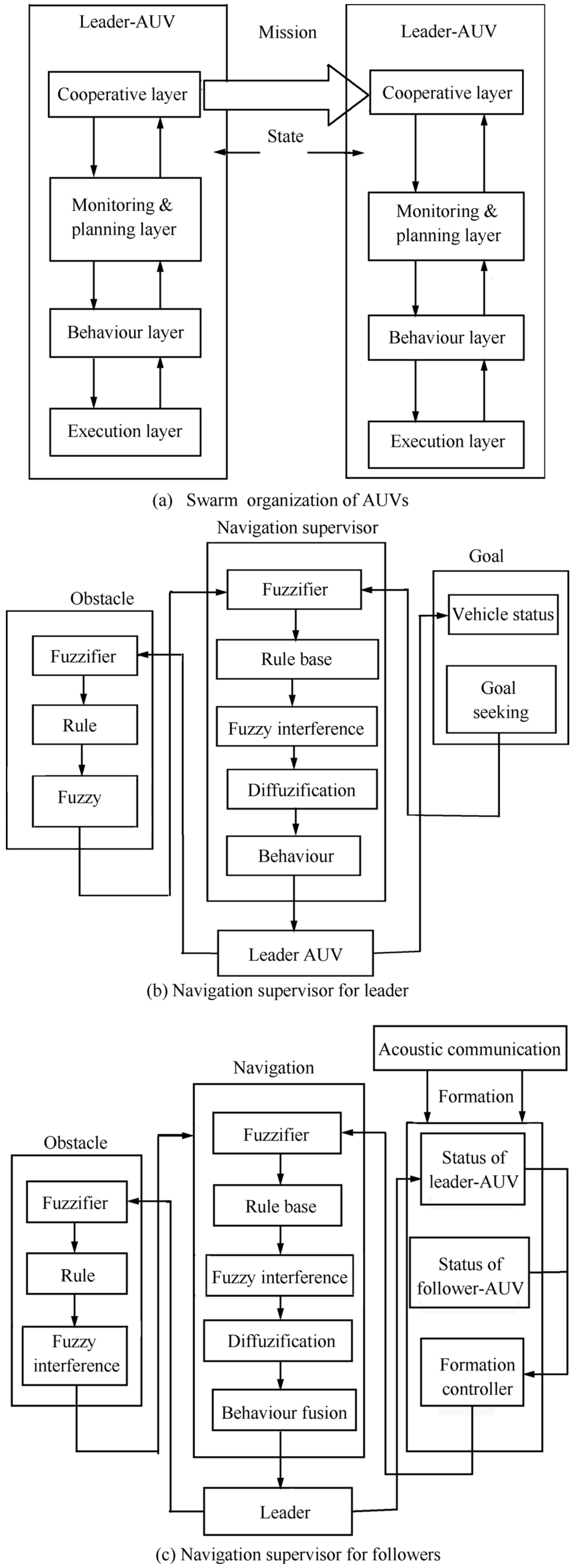
Fig. 26 Path following of i-th AUV with communication losses

4.2.4 Fuzzy logic based behavior fusion for multi-AUV formation keeping in uncertain ocean environment

This section presents a new behavior fusion method using fuzzy logic for coordinating multiple reactive behaviors as shown in Fig. 27[27]. The inputs to the proposed fuzzy control scheme for the leader AUV in multi-AUV system consist of the deviation in yaw angle while performing obstacle avoidance and goal seeking action separately, and the fuzzy control scheme for the follower AUV consists of the deviations in yaw angle while performing obstacle avoidance and formation keeping action separately[86].

4.2.5 Synchronized path following control for multiple under actuated AUVs

The synchronized path following based control laws are categorized into two envelopes such as: 1) steering individual AUV to trace along predefined paths, 2) ensuring tracked paths of multiple AUVs to be synchronized, by



(a) Swarm organization of AUVs

(b) Navigation supervisor for leader

(c) Navigation supervisor for followers

Fig. 27 Fuzzy logic based multi-AUV formation[27] means of decentralized speed adaption under the constraints of multi-AUV communication topology as shown in Fig. 28[87, 88]. With these two tasks formulation, geometric paths following are built on Lyapunov theory and back-stepping techniques for a class of individual path following control[89−91]. Synchronization of path parameters are obtained by using a mixture of tools from linear algebra, graph theory and control theory[8, 77, 92].

4.2.6 Decentralized overlapping tracking control of a formation of AUVs

This method is a new methodology based on the expansion and contraction paradigm as presented. The methodology is based on a specific linear formation model. Decentralized controllers for the extracted subsystems are contracted to the original position accordingly as shown in Fig. 29. The dynamic output feedback control law based on decentralized observers may also be used as shown in Fig. 30[93−95].

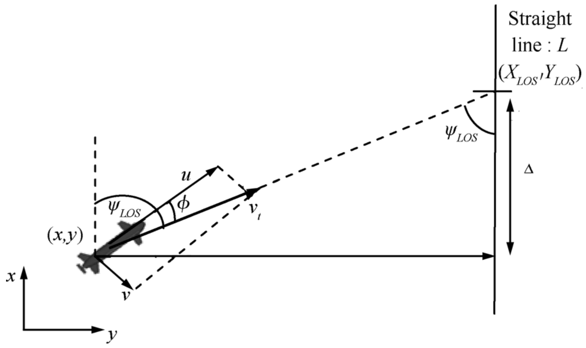


Fig. 28 Synchronized path following control

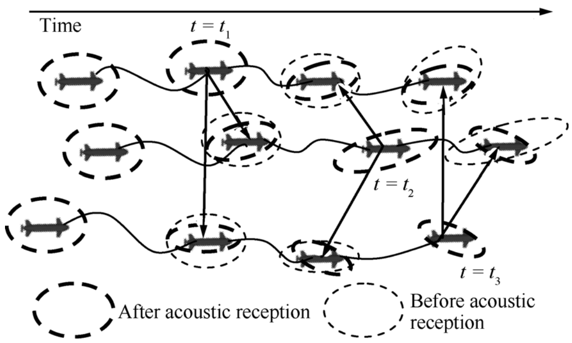


Fig. 29 Decentralized tracking control of multi-AUV formation

4.2.7 Nonlinear cross-track control of an underactuated AUVs

The stabilization function of the yaw angle is designed to stabilize the cross-track error as the virtual input, resulting in the cascaded subsystems of the cross-track and the yaw tracking as shown in Fig. 30[40]. For the normal cross-track subsystem when the yaw and yaw rate tracking errors are zeros, the control parameter condition is derived to make the cross-track error and the sway velocity globally asymptotically stable[96].

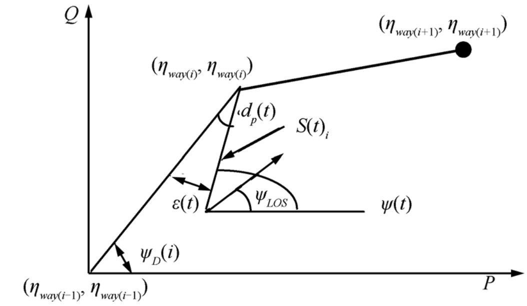


Fig. 30 Nonlinear cross-track control of an underactuated AUVs

$$\psi LOS = \arctan\frac{Y_{way(i)} - y(t)}{X_{way(i)} - x(t)}. \tag{15}$$

Suppose that the current navigation angle of AUV is $\psi(t)$, the position in inertial frame is $(x(t), y(t), \psi_d(i))$, where $\psi_d(i)$ is the angle of the current line of tracking[96], i.e.,

$$\psi_d^i = \arctan\frac{Y_{way(i)} - Y_{way(i-q)}}{X_{way(i)} - X_{way(i-q)}}. \tag{16}$$

The navigation tracking error is given by[96]

$$\psi(t)_{CTE(i)} = \psi_d(i) - \psi(t). \tag{17}$$

The distance from current AUV to the next way point is[96]

$$S(t)_i = \sqrt{X(t)^2_{way}(i) + Y(t)^2_{way(i)}} \tag{18}$$

where $X(t)_{way(i)} = X_{way(i)} - x(t)$ and $Y(t)_{way(i)} = Y_{way(i)} - y(t)$[96].

Then, the cross tracking error $\varepsilon(t)$ is given by

$$\varepsilon(t) = S(t)_i \sin(d_p(t)) \tag{19}$$

where

$$d_p(t) = \psi_{LOS} - \psi_d(i). \tag{20}$$

4.2.8 Nonlinear formation-keeping and mooring control of multiple AUVs

A nonlinear formation keeping and mooring control of multiple AUVs is proposed in [97]. The AUV formation under consideration is constrained by the desired separations and orientations of follower AUVs with respect to a time-varying leader AUV as shown in Fig. 31[98]. The process uses as follows.

1) A time-varying, smooth feedback control law for the formation-keeping of multiple non-holonomic AUVs is proposed.

2) A time-varying, smooth feedback control law with asymptotic stability is designed to collaboratively moor the follower AUV to its desired docking position and orientation with respect to the leader by using the integrator back stepping method.

3) The realization problems of physical AUV system and singularity avoidance are investigated for applying the aforementioned control laws to a real formation system of AUVs.

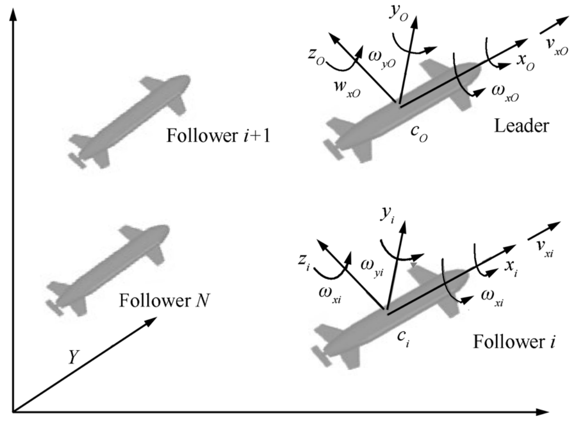


Fig. 31 Schematic of the leader–follower formation of AUVs[97, 98]

4.2.9 Finite-time consensus algorithms for multiple AUVs

Based on homogeneous control method, finite-time consensus algorithms are proposed for both leaderless and leader-follower multi-AUV formation[99, 100]. In the leader-follower case, a distributed finite-time observer is developed for the followers to estimate the leader′s velocity. In the cooperative control problems of multi-agent systems, all the agents reach the agreement on a common state by implementing appropriate consensus protocols. Due to the above superiorities and the role of the consensus problem in distributed cooperative control field, several kinds of finite-time consensus algorithms have been developed for both first-order and second-order multi-agent systems recently as shown in Fig. 32[101].

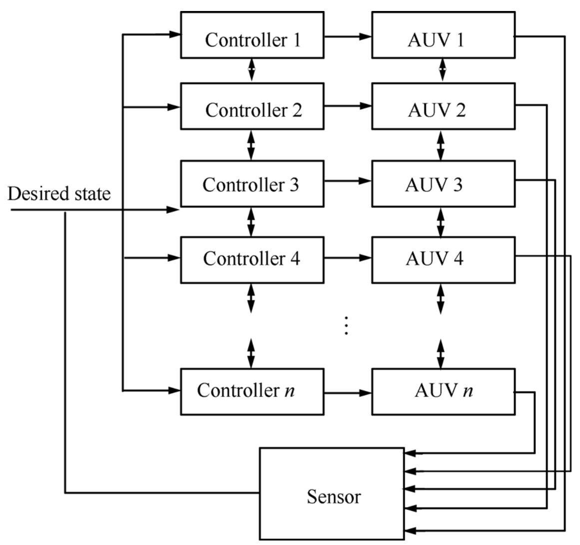


Fig. 32 Coordination of AUVs through distributed approach

4.2.10 Range-based formation control

In this formation only ranges are obtained from the leading AUVs without knowledge of the formation path shown in Fig. 33.

4.2.11 Hierarchical control system

The particular AUVs used for the surveillance task are equipped with direction finding sensors and communication payloads. One particular motivation for the research is accurate cooperative localization of radar systems with a small AUV fleet[102, 103].

In a hierarchical structure, control tasks are classified and distributed non-uniformly among agents. A commonly used hierarchical structure within the formation control literature is the leader-follower structure. In the leader-follower structure, one "leader" agent is provided with direction and/or path information and is responsible for path tracking, manoeuvring and guiding tasks. The other "follower" agents within the formation measure their distances and/or bearings to a set of "leader" or "follower" agents or both, and are usually required to maintain the shape of the formation via keeping certain fixed distances as shown in Fig. 34[50, 104].

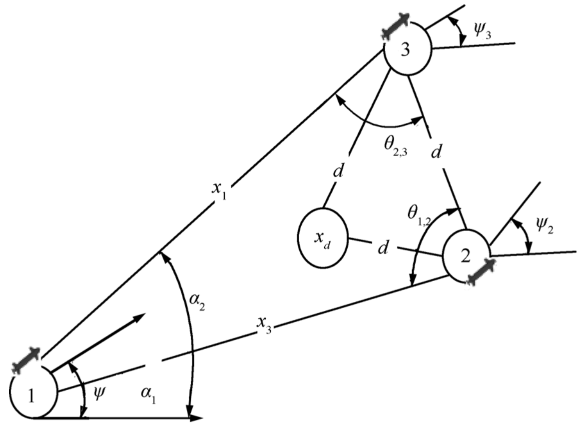


Fig. 33 System of three AUVs and their intended triangular formation

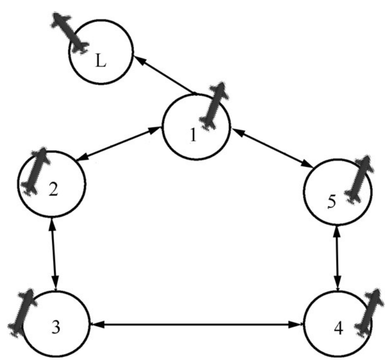


Fig. 34 Network topology for a group of agents with a virtual leader

4.2.12 Passivity based approach

In this section, the formation control problem of AUV under the passivity-based group coordination framework is proposed in [105]. A consensus tracking approach is also proposed. The desired formation patterns are obtained when the common reference velocity assigned by a dynamic virtual leader is available to only one AUV or one subset of AUVs[106]. A comparison study is made on various trajectory tracking based formation control strategies as provided in Table 2.

Table 1 Comparison of various regulatory formation control strategies

Formation technique	Control strategy	Control variable	Complexity level	Advantage	Disadvantage	Applications
Gateway coordination	Feed-back linearization	Yaw (ψ)	Simple	Knowledge of each AUV's position makes the formation keeping easier	If any one AUV gets damaged, the whole formation gets affected	It is used for monitoring pipeline surveillance
Neighbour's reference	Decentralized co-operative control technique	Position vector (η)	Simple	Each AUV communicates to its immediate neighbours for coordination	Communication delays between neighbours are inevitable	Coordination of a school of robotic fish
Centralized approach	Centralized cooperative control technique	Position vector (η) velocity vector	Complex	Power efficient as single computer or less number of sensors are used for monitoring	Communication delays are inevitable High computational power and not robust	Naval mining search operations
NN based dynamic surface control	Adaptive control technique	Position vector (η)	Complex	Reduces the equipment cost and the network burden	Affected by environmental disturbances Dependence on a single controller	Underwater survey Used in arctic region research
Followers within a cluster	Centralized control	Position vector (η)	Simple	AUVs communicate among themselves	Communication delays are inevitable	Formation of mobile AUVs
Spatially synchronized parallel formation	Co-operative synchronized control	Velocity vector	Simple	It is a parallel formation Affected by communication delays	Difficult to discover AUV if any one of the vehicles gets damaged	Distance fixing and observation synchronization
Non-hierarchical control	Periodic formation control	position vector (η)	Simple	Distance maintaining and path tracking are uniformly distributed due to agents	Communication delays are inevitable	Underwater survey collision and obstacle avoidance
Stationary surveillance with formation change	Adaptive control	Phase waves phase gradient	Complex	Formation shape may be switched	Communication delays are inevitable	Underwater survey
Cross-track formation	Line of sight guidance	Velocity	Simple	Flexible and easier	Communication delays are inevitable	Collision and obstacle avoidance
Geometric formation	Velocity optimization	Velocity & position	Simple	Very easy Practicable	High computational power	Distance fixing and observation synchronization
Boundary-based geometric formation	Region boundary technique	Position vector (η)	Simple	Effective to carry out individual task.	High computational power	Edge-based segmentation approach is used for pipeline inspection.
Behavioural approach	Behavioural technique	Coordinate (η)	Complex	Guide AUVs in an unknown and uncertain environment	Mathematically more complex Not much practicable	Goal seeking Obstacle avoidance
Genetic algorithm	Path planning technique	Yaw (ψ)	Complex	Overcome disadvantages of memory consumption and Octree approach	High computational power	Practical aquatic survey Studying underwater environment

Table 2 Comparison of various trajectory tracking based formation control strategies

Formation technique	Control strategy	Control variable	Complexity level	Advantage	Disadvantage	Application
Virtual leader follower hierarchy structure	Decentralized controller	Position vector (η)	Simple	Relatively easy to understand and implement	No feedback from the followers	Underwater survey
Coordinated control in the presence of communication losses	Decentralized controller	Position vector (η)	Simple	Formation can still be maintained even if the leader is perturbed by some disturbance	Lack of robustness	Aquatic research work
Fuzzy logic based behaviour	Fuzzy Logic based controller	Yaw (ψ)	Simple	Reduces the total huge task to individual small tasking problems	Leader is a single point of failure	Swarm mobilization of AUVs
Synchronized path following control	Decentralized back-stepping technique	Position vector (η)	Simple	Independent of geometry of formation No chance of fault in existing or switching on formation shapes	Difficult to design a controller such that all the optimized points except for the desired equilibrium one are unstable	Naval operations and underwater missions using multiple under actuated AUVs
Decentralized overlapping tracking	Expansion and contraction paradigm	Position vector (η)	Simple	Reduces the controller′s computational power Independent of any central controller Effective when the communication is limited	Unable or extremely difficult to predict and control the critical points Very sensitive to external disturbance	Underwater tracking activities Underwater mine detection
Nonlinear cross-track control	Decentralized control technique	Yaw (ψ)	Simple	Easy to implement this controller Independent of geometry formation	Difficult to predict and control the critical points	Arctic missions Deployment of underwater missiles
Nonlinear formation-keeping and mooring control	Back-stepping control technique	Yaw (ψ) velocity	Complex	AUV only transmits state information to its neighbour vehicle	Neighbour to neighbour communication is required	Used in establishing proper docking position and orientation
Finite-time consensus algorithms for AUVs	Consensus based technique	Position vector (η) velocity	Simple	Effective when the communication among the AUVs is limited	Underwater communication is prior issue which is complex	Used in first order and second order multi-agent systems (MAS)
Range based formation control	Accurate cooperative localization	Position vector (η)	Simple	Communication is usually asynchronous and locally transmitted	Very sensitive to external disturbance Basically model based	Path tracking Maneuvering and guiding tasks
Passivity based tracking	Consensus tracking approach	velocity	Simple	Possible to avoid the problem caused by multiple packet transmission	Very difficult to solve any formation problem by individual AUV in the group	Small AUV fleet formation control Tracking activities

5 Challenges in formation control

There are several challenges associated with formation control of multiple AUVs. These are classified as wave disturbance, communication constraints, collision and obstacle and may be affecting trajectory tracking, path following, formation shape generation, switching between shapes and path generation for multiple AUVs[107]. These are briefly explained below.

5.1 Environmental disturbance

For an AUV to operate with a high degree of reliability, disturbances and their effects on the AUV must be modeled such that adequate degree of accuracy must be achieved[22]. The main sources of the dynamic disturbances encountered by AUVs are wave and current induced disturbances. The design of AUV model in presence of wave disturbance forces in shallow water is necessary to generate a dynamic model representing the wave induced water velocity and acceleration[107]. Underwater external sea current disturbances are considered to be external factors causing a cross tracking error. To develop such model, the major effects of oceanic currents on dynamical model of AUV in coastal areas come from tidal currents and Stokes′s drift effects[108].

5.2 Communication constraints

A wireless network is necessary for each AUV to keep the information of its neighbor AUVs as well as to maintain global communication[109]. While moving in formation, the AUVs should communicate with each other through a modulator/demodulator(MODEM) fitted in AUV according to the control and coordination strategies of the system[110]. Within communication range, if the two AUVs are locally communicated then perfect communication channel exists directly but the communication among them is possible by observing the states of the AUVs then this type of communication is non line of sight (NLOS) communication[111]. If an AUV can communicate with any other AUV within communication range, then it is called global communication. Positions of the AUVs within formation are determined according to desired formation shape based on communication topology[112]. For AUV communication, acoustic signals may be used without using electromagnetic waves. The chances of multipath propagation between the AUVs are due to disturbances of sea layers, small bandwidth, and strong attenuation of signal in underwater medium, and high latency due to the low speed (1500 m/s) of sound in water[113]. Thus the data transfer rate is very low in under sea area. During motion of a formation group, when information flows from one AUV to another, there may be chance of data packet loss and/or dropout due to attenuation in the environment and scattering of the information wave in the surrounding. So there is a chance of occurrence of delay. Thus delay compensators can be employed while designing formation control strategies. In formation control of AUVs, graph theory is necessary for communication of different AUVs with each other[114]. Here, the vertices are placed at the position of AUVs and the links are formed by the directed vectors from one AUV to another[115]. To overcome the limitations of underwater environment and to create the efficient cooperation among the multiple AUVs, a special type of system DELPHIS may be used[116,117]. The control and communication based on multimode operation may be used to build up a prototype[118]. To keep the communication among the fleet of cooperative AUVs, an inter-vehicular communication system may be used with environmental study[119]. Each node uses more communication range as much as possible. Network algorithm based on time-scheduled operation may be developed to locate the AUV in underwater[120]. The localization of AUVs is possible by measuring the inter-vehicular propagation delay and by exchanging localization map within water. To use efficiently the low data rate in acoustic communication for AUVs, compact control language (CCL)[121], or linear quadratic (LQ) optimal control are employed where the control algorithm based on onboard computing power[122, 123] may be used. Navigation problems of AUVs can be solved to some extent by using the acoustic transponder navigation systems. It is cost effective with additional advantages of global positioning systems (GPS).

In case of underwater networks, routing design for adhoc routing for wireless radio networks, is still being a challenging issue. Distributed protocols are proposed for both delay-sensitive and delay-insensitive applications and allow nodes to select the next hop with the objective of minimizing the energy consumption while taking into account the specific characteristics of acoustic propagation as well as the application requirements[115, 119]. A geographical approach is also proposed by Leonard et al., where a theoretical analysis has shown that it is possible to identify an optimal path that the mobile nodes may try to achieve by minimizing the total path energy consumption[1]. Other approaches include pressure routing, where decisions are based on depth, which can be easily determined locally by means of a various sensors[109].

5.3 Collision and obstacle

When a group of multiple AUVs move in formation, it is necessary to avoid collision between themselves as well as avoid collision with the solid obstacles intersecting the formation path to be travelled by the group[124].

Obstacle avoidance is highly essential issue in formation control. The obstacle may be static or dynamic[125]. For collision avoidance between AUVs, there must exist a repulsive force between them[126]. Similarly, a repulsive force should be established between AUV and the obstacle such that there is no collision between the static obstacles appearing on the desired path as shown in Fig. 35. AUVs should avoid collision with the obstacle and should keep a $\lim_{t\to\infty} \|\eta - \eta_{obs}\| = d_s$ safe distance from the obstacle. Where $\eta_{obs} = [x_{obs}, y_{obs}, \psi_{obs}]^{\rm T}$ is the position of the obstacle, d_s is the safest distance of the AUV form obstacle. Some of the best methods for avoiding collision between an AUV,

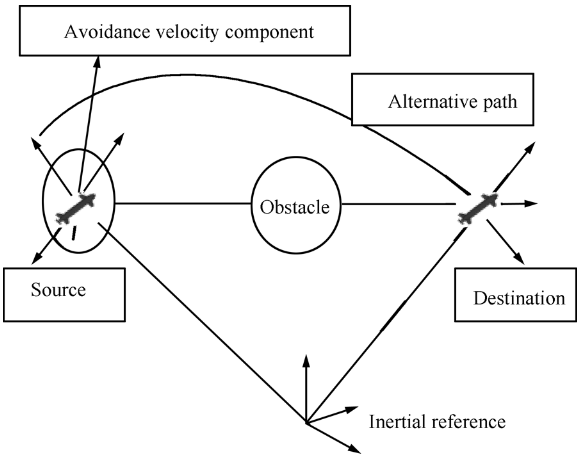


Fig. 35 Line-of-sight and collision avoidance path components[125]

its neighbors and obstacles are discussed below.

5.3.1 Artificial potential function based approach

In this method, a repulsive potential function between AUV and obstacle is developed which is inversely proportional to the norm of the distance between them[127, 128]. So when the distance between the AUV and the obstacle decreases, the repulsive force increases and vice versa[129]. To design the obstacle avoidance algorithm, the maneuvering area is divided into three zones: safe zone, avoidance zone and danger zone. The total potential energy is divided into two different parts: One is potential energy between the two AUVs and the other is potential energy between the vehicle and the target.

5.3.2 Soft computing based approach

Mixed integer quadratic programming (MIQP) optimization method may be used to detect and avoid collision between the vehicles[130, 131]. This paper describes a heuristic search technique carrying out collision avoidance for autonomous underwater vehicles (AUVs). In [132], the search technique adopts fuzzy relational products to conduct path-planning of intelligent navigation system. For verification, it is compared with A* search method through simulation time, the optimization of path and the amount of memory usage. Bui and Kim[133] proposes a new heuristic search technique for obstacle avoidance of autonomous underwater vehicles which uses the Bandler and Kohout′s-product of a fuzzy relation with a sonar partitioned into seven sections, this method enables AUVs to navigate safely through the obstacle to the goal with the optimal path.

The fuzzy relation between the sonar sections and the properties of a real-time environment is used as a core concept. In [134], a new-style fuzzy inference controller is proposed to address the mentioned problems for AUV path planning and hence a moving obstacle avoidance strategy is developed. In order to get precise fuzzy membership functions, PSO algorithm with strong global optimization ability is employed to tune them, then improve the performance of the proposed fuzzy controller and achieve a reasonable shorter and smoother path to the target[135].

Fuzzy logic and artificial neural network based controller is used in [136] to control an autonomous underwater vehicle to avoid obstacles as shown in Fig. 36. The controller can adjust itself to the variations of oceanic environment. In [137, 138], a collision avoidance algorithm is presented based on principles of reinforcement learning and also motion characteristics of an AUV system. Here, a stochastic real value reinforcement learning algorithm for learning functions with continuous outputs is proposed. Here, the obstacle avoidance mission is divided into two parts, i.e., targeting and avoiding behaviour.

5.3.3 Virtual potential based collision avoidance

In [139], a navigation algorithm is presented, which integrates virtual force concept with a potential-field-based method to maneuver AUV in unknown or unstructured environments. The study focused on the free local minimum in potential-field based navigation.

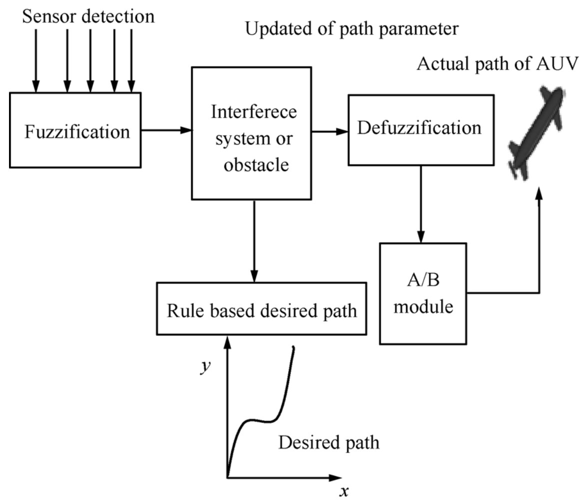


Fig. 36 Fuzzy controller based tracking control to avoid obstacles[136]

5.3.4 A real-time obstacle avoidance using a multi-beam forward looking sonar

In [140], a real-time obstacle-avoiding expert AUV system based on a multi-beam forward looking sonar is presented. Expert system is designed based on the information of task execution. The inference engine is designed and implemented according to the images of sonar, which can send algorithm for obstacle avoidance and path re-planning[141−145].

5.3.5 DVZ approach

In [146], a theoretical study of the coordination of the geometrical movements of AUVs formation following a trajectory forming a desired geometrical structure is presented. It is possible to compute the deformation between the real formation of AUVs and a desired formation which helps us to compute the movement that every vehicle should make to obtain zero deformation. An approach namely deformable virtual zones (DVZ) is used in [147] to resolve all the constraints in a homogeneous way and supply a command vector for each vehicle.

5.3.6 Mission planning under dynamic obstacle avoidance

The proposed method is an application of the Markov-decision-process (MDP) based motion planning method for managing both the kinematics and dynamics of an AUV affected by sea flow and obstacles[148]. The real-time obstacle avoidance needs preplanning when a new obstacle is discovered so that the AUV can find a suitable path around concave obstacles[149].

5.3.7 Limit cycle process

A method based on limit cycle process may be employed for avoiding obstacles by generating trajectories of the robot manipulators[150]. Here the shapes of complex obstacles are modeled by unstable limit cycles. The obstacles may be avoided using the same limit cycle method but in a different fashion, as in [151]. Here the trajectories of the obstacles are presented as a set of transitional trajectories which are considered as the solutions of the differential equations presenting a stable limit cycle of elliptical shape. These ellipses encircle the obstacles. When an obstacle is detected on the desired path, the new trajectories of the vehicle are generated satisfying those differential equations to avoid the obstacle. When the obstacle is avoided, the vehicle again retunes to the original path. By combining this avoidance strategy of individual obstacle, a group of AUVs in formation can avoid obstacles during travelling along the desired trajectories[152, 153].

Energy problem in the case of most AUVs is a traditional problem. The batteries which provide energy contain silver-zinc composition or lead-acid composition. But now commercial nickel metal hydride (Ni-MH) batteries are available which can provide more energy. Another way of solving this problem is using of solar cells as supplementary energy sources. This can increase the endurance of the energy cells.

6 Formation control stability

Assumption 1. The dynamics equations (5)−(12) of AUV provides the following properties[1, 154−162].

1) M_η is symmetric positive stable for any number of AUVs, $i \in (1, 2, 3, \cdots, N)$

$$\lambda_{\min}(M_i)\left\|x\right\|_2^2 \leq x^{\mathrm{T}} M_\eta(\eta_i) x \leq \lambda_{\max}(M_i)\left\|x\right\|_2^2, \ \forall x \neq 0. \tag{21}$$

2) C_η is a skew symmetric and which can be termed as[1]

$$x^{\mathrm{T}}\left(\frac{1}{2}\dot{M}_\eta(\eta_i) - 2C_\eta(\eta_i, \dot{\eta}_i)\right)x = 0, \ \forall x \in \mathbf{R}^3. \tag{22}$$

3) The damping matrix $D_\eta(\eta_i, \dot{\eta}_i)$ is positive such that[1]

$$x^{\mathrm{T}} D_\eta(\eta_i, \dot{\eta}_i) x > 0, \ \forall x \neq 0. \tag{23}$$

4) Embedding a load will not only change the mass matrix, but will also induce torques as the gravity and buoyancy centers will not coincide anymore and hence g will change[1]. But as it is considered for three DOF of motion along (x, y) axis, hence $g(\eta_i) = 0$.

5) Centre of mass and centre of buoyancy coincide with each other and other terms such as roll motions and hydrodynamic terms of higher order are assumed to be negligible[1].

Formation control is the control of interconnected system of multiple AUVs. For safety, robustness as well as for getting desired performance from an interconnected system, stability analysis of the system is necessary. This is essential to make a system operationally stable. There are three stability notions of formation control. These are string stability, mesh stability and leader-to-formation stability which are interconnected to each other.

Assumption 2. An interconnected nonlinear AUV system is called look-ahead, if the (i, j)-th subsystem is connected only to the subsystems (k, l) such that $k \leq i$ and $l \leq j$. The look-ahead condition may be defined as in [163−172].

Consider a system of the form[173]

$$\dot{\eta}_i = f_i\left(\eta_i, \eta_{i-1}, \cdots, \eta_N\right) \tag{24}$$

where $i \in (1, \cdots, N)\,, \eta_i \in \mathbf{R}^n, f : \mathbf{R}^n \times \cdots \times \mathbf{R}^n \to \mathbf{R}^n$ and $f\left(0, \cdots, 0\right) = 0$.

Assumption 3. Consider the state ξ of leader-follower formation and the formation performance output z. The formation state is obtained from the original state vectors of the AUV and controllers by a coordinate transformation[173−183].

$$\xi = \chi(t, z) \tag{25}$$

where $\chi \triangleq (\chi_1, \chi_2, \cdots, \chi_N)$. The performance output z is a function of the formation state. The closed loop formation dynamics then are given by

$$\begin{aligned} \dot{\xi} &= f(t, \xi, d) \\ z &= h(t, \xi) \end{aligned} \tag{26}$$

where $f\left(0, \cdots, 0\right) = 0$ and $h(t, 0) = 0$ for all t. The following conditions for formation (25) must be satisfied, if

1) the system (25) has well defined solution for all $t \geq 0$, with initial conditions $\xi\left(t_0\right)$;

2) all solutions of (24) must satisfy

$$\begin{aligned} &\left\|z\right\|_\infty \leq \max\left\{\rho\left(\left\|\xi\left(t_0\right)\right\|\right), \lambda\left(\left\|d\right\|_\infty\right)\right\} \\ &\lim_{x\to\infty}\sup\left\|z\left(t\right)\right\| \leq \lambda\left(\lim_{x\to\infty}\sup\left\|d\left(t\right)\right\|\right) \end{aligned} \tag{27}$$

where $\left\|z\right\|_\infty \triangleq \sup_{t\geq 0}\left\|z\left(t\right)\right\|$.

Assumption 4. This type of stability criteria are used to check the stability of the systems operating in platoon structures or hybrid platoon system which obeys the look-ahead conditions. This stability method can be applicable to both constrained and unconstrained systems. The stability criteria are applied in an array of linear interconnected AUVs under communication constraint condition in [77, 183−192]. String stability presents the uniform boundedness of the states of all interconnected systems. Mesh stability is used for ensuring stability property by considering attenuation of error of multiple interconnected AUVs. The origin $\eta_i = 0$, $i \in N$ of (23) is string stable if for a given $\in > 0$, there exists a $\delta > 0$ such that the following condition is satisfied[173]

$$\|\eta_i(0)\|_\infty < \delta \Rightarrow \sup_i \|\eta_i(\cdot)\|_\infty < \in . \quad (28)$$

The origin $x_i = 0$, $i \in N$, of (23) is exponentially string stable if it satisfies the condition of string stability and $\eta_i(t) \to 0$ asymptotically, $\forall i \in N$. For a step change in $\dot{q}_L$ at any time $t = 0$, the leader-follower interconnected system will be asymptotically stable if the following condition is satisfied. For every $j = 2, \cdots, N_v$, there exists a constant $\alpha_j \in (0, 1)$ so that the following closed-loop position error satisfies[173]

$$\max_{t\geq 0} |q_{j,e}(t)| \leq \alpha_j \max_{t\geq 0} |q_{1,e}(t)|, \forall j = 2, \cdots, N_v. \quad (29)$$

Leader-follower string stability

$$\max_{t\geq 0} |q_{j,e}(t)| \leq \alpha_j \max_{t\geq 0} \left|q_{(j-1),e}(t)\right|, \forall j = 2, \cdots, N_v. \quad (30)$$

Predecessor-follower string stability

$$\max_{t\geq 0} |q_{j,e}(t)| \leq \alpha_j \max_{t\geq 0} \left|q_{(j-1),e}(t)\right|, \forall j = 2, \cdots, N_v. \quad (31)$$

q_L and $\dot{q}_L$ are the geometric position and speed of AUVs. For Mesh stability, the dynamical system (23) is globally exponentially mesh stable if the following conditions are satisfied, given $\in > 0$, there exists a $\delta > 0$ such that[173]

$$\|x(0)\|_\infty < \delta \Rightarrow \|x(t)\|_\infty < \in \quad (32)$$

$$x \to 0, \text{ exponentially } \forall x \in \mathbf{R}^n \quad (33)$$

$$\|x_i(t)\|_\infty \leq \|x_i(t)\|_\infty^{i-1}, \forall i \in \{2, \cdots, N\}. \quad (34)$$

7 Applications of formation control of AUVs

Most of the applications of AUV require that it should follow a desired path or surveillance of a desired region. AUVs are now being used for tasks with roles and missions based on navigation system, guidance system and control structure as shown in Fig. 37.

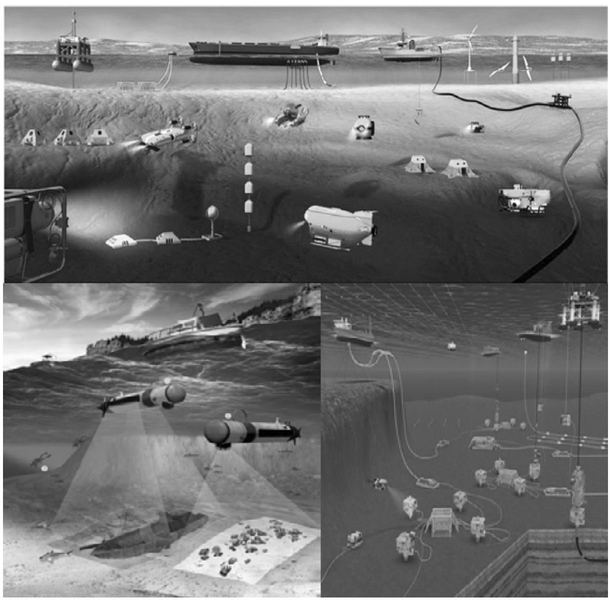


Fig. 37 Applications of multiple AUVs in formation[32, 33]

7.1 Guidance system

The guidance system helps to determine the path generation from AUVs with the help of current position to the desired position. The feasible path will differ for different AUVs depending on fully-actuated or underactuated system. It is necessary for the AUV to follow the desired path successfully considering the obstacles across the paths[34, 193−202].

7.2 Control structure of AUV system

Control structure determines the required control forces necessary for steering the AUV along the desired path[203−205]. Control structure based on requirement is divided into trajectory tracking, path following and way point tracking[206−208]. While developing a control law, it is necessary to check the generated control forces which should reside within desired limit[209−211]. The motion control strategies to accomplish the mission of AUVs are classified as trajectory tracking, path following and way point tracking[35, 212−215].

AUVs are employed in missions such as oceanographic observations, bathymetric surveys, ocean floor analysis, military applications, recovery of lost objects, etc[36]. The applications of underwater vehicles have shown a dramatic increase in recent years, such as mines clearing operation, feature tracking, cable or pipeline tracking and deep ocean exploration. The mission areas include commercial applications by surveying of the sea floor for oil and gas industry, mine countermeasures, monitoring and safeguarding protected areas and oceanic research. AUVs are also employed for military purpose such as anti-submarine warfare, to aid in the detection of manned submarines[216].

8 Conclusions

For decades, AUVs have been widely used for many tasks. The ruthless and unstructured nature of the underwater environment causes significant challenges for underwater autonomous systems. This paper presents a comprehensive review on the current control issues on a group of AUVs. For decades, formation control has become an active research topic and has broad applications in Robotics. The formation control algorithms are subdivided based on the technical approach, controllers used, level of coordination and communication constraints. The paper has also highlighted some areas for future work in the field. Recent advances in stability analysis have been developed for rapid improvement of formation control. In addition, some basic challenges and applications have been presented. The paper also informs briefly a new consideration on formation control stability which has a promising future research direction.

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