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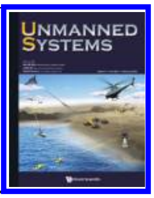

A Survey on Formation Control Algorithms for Multi-AUV System

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With the development of autonomous underwater vehicle (AUV) application techniques, formation control of multiple AUVs becomes a worldwide research focus. In this paper, first, formation control methods are summarized as: virtual structure method, behavior-based method, leader–follower method and artificial potential field method. Second, the peculiarities and difficulties of formation control especially for multi-AUV system are analyzed based on the research and development status in this area. The critical technical problems are summarized into three aspects: problem of AUV's dynamic complexity; problem of environmental complexity; problem of severe underwater communication constraints. Finally, the major development trends of multi-AUV system are discussed.

Keywords: Formation control; virtual structure; artificial potential field; leader–follower.

1. Introduction

An autonomous underwater vehicle (AUV) is a highly autonomic device which has no physical connection to the mother ship and can accomplish the given tasks with its own control and guide system in three-dimensional (3D) underwater environment. With the increasing complexity of tasks, it is necessary to carry out underwater missions which are beyond the capacity of a single AUV through cooperation of multiple AUVs. In certain missions, the AUVs should move collectively as a formation. Formation control is a technology to control a group of AUVs moving along a desired path as the task requires, while maintaining desired formation patterns, and adapting to the environmental constraints, such as obstacles, limited space, ocean current and communication constraints. In order to work in specific environments or meet the demands of some jobs, a variety of geometric formations could be adopted by multi-AUV system. Typical geometric formations include line, triangle, diamond, wedge and polygon as shown in Fig. 1.

In the early studies, most attention has been paid on the flying formation control of aircrafts, also some on the formation control of ground mobile robots system. In recent years, more and more scholars move their focus on the formation control of multi-AUV system. Although multi-AUV system has unique characteristics as long as the working environments are totally different from that of aircrafts or ground mobile robots, some traditional formation control strategies have still been transplanted and modified to be applied on the underwater vehicles. On the basis of the present development of formation control at home and abroad, the formation control methods of multi-AUV system are classified as virtual structure (VS) method, behavior-based method, leader–follower method and artificial potential field method. In addition, the main difficulties of formation control especially for multi-AUV system are analyzed. Multi-AUV system is used in the underwater environment, where the dynamic characteristics are different from air and ground environment, so that some formation control strategies could not be simply adopted and could not be reduced to the several traditional types. After making a survey on the traditional formation control, this paper summarizes the underwater formation control methods in a novel way which is according to the three aspects of critical technical problems considering the special issues for formation control of multi-AUV system, and finally makes a

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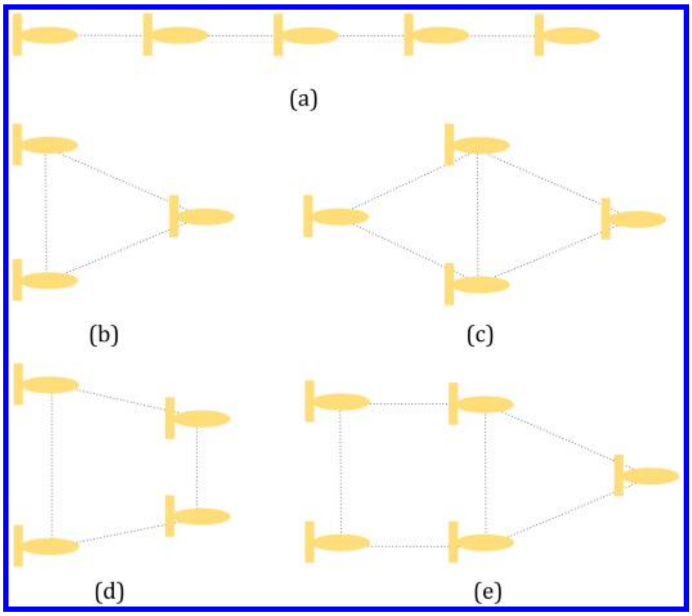

Fig. 1. Typical geometric formations. (a) Line, (b) triangle, (c) diamond, (d) wedge and (e) polygon.

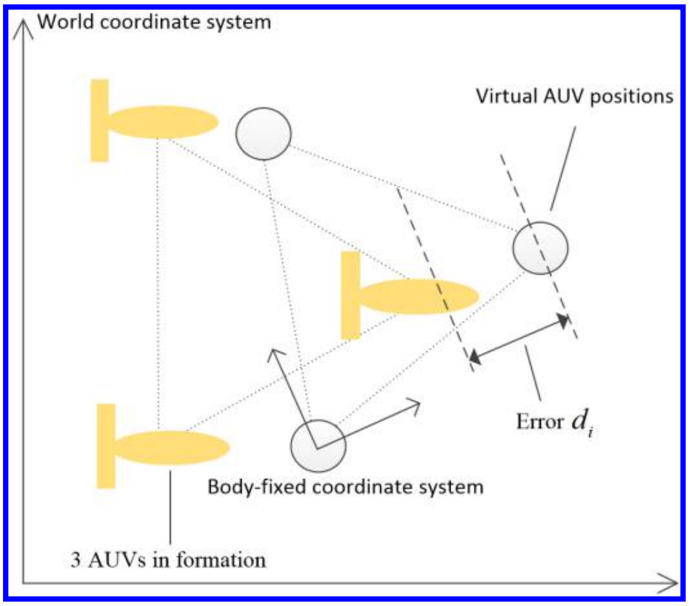

Fig. 2. Geometry of the VS definition and the AUVs in formation.

conclusion about the possible development trends for future studies in this research field.

2. Algorithms for Multi-AUV Formation Control

Formation control of multiple vehicles has been identified as a key technology for the future and studied by many researchers in recent years. According to concurrent research results, there are much fewer literatures on the formation control of multi-AUV systems than on aircrafts or mobile robots systems. Fortunately, a considerable amount of methods originally implemented in the air or on the land could be used under water after some modifications. Algorithms for multi-AUV systems are partly originated from the traditional formation control methods for aircrafts or mobile vehicles. This section summarizes the traditional approaches applied to both multi-AUV systems and other multiple vehicles systems. The various control methods reported in former literatures could be categorized into four groups: VS schemes, behavior-based methods, artificial potential field techniques and leader–follower schemes.

2.1. *Virtual structure schemes*

To form and maintain a certain geometry between multiple robots, a rigid structure formed is introduced as a reference, where an ensemble of robots behave as if they were particles embedded in the rigid structure which is named VS, as shown in Fig. 2. This scheme conventionally includes four operations: (1) define the desire dynamics of the VS and align the VS with the current robot positions; (2) move the VS in a given direction; (3) compute individual vehicle trajectories to move the vehicle to the desired VS point as the corresponding AUV contributes an error of d_i; (4) adjust vehicle velocities to follow the desired trajectories, at the same time, maintain a rigid geometric relationship among the mobile vehicles. This algorithm implements the preceding four steps in sequence repeatedly until the formation of vehicles reaches the desired position.

The earlier form of this method without formation feedback is sensitive to environmental disturbance [1]. Ren and Beard [2] introduces formation feedback from the spacecraft to the VS. This formation feedback algorithm improves the performance of the system and decreased maneuver errors, which makes formation-keeping more robust to the uncertainty both internal and external. A coordination architecture that subsumes VS approach and other methods is introduced to the multi-agent coordination problem in [3]. VS method is often applied to the overall architecture design of the controller, and is suitable to the distributed system or nonholonomic mobile vehicles network, which include a large number of vehicles with stringent communication limitations [4, 5]. In [6], the kinematics and dynamics of multiple mobile robots with skidding and slipping effects are considered, and the formation control scheme is derived from the VS approach where the reference trajectories consisting of path parameters are employed to satisfy both the tracking control and the formation maintenance.

The main advantage of the VS approach is that it is fairly easy to prescribe the coordinated behavior for the whole formation group, and add a type of robustness to formation through the use of formation feedback. Thus, the formation can be maintained very well while maneuvering. The disadvantage is that requiring the formation to act as a rigid VS limits the class of potential applications. So far, this method is only for the two-dimensional (2D) environment.

2.2. *Behavior-based methods*

Behavior-based method in formation control decomposes the formation task into a series of basic behaviors of the robots. In formation control, there are four basic behaviors: following-wall, avoiding the obstacle and other robots, maintaining the formation and moving to the target. The behavior-based control gives these behaviors a priority from high to low. According to the distance to the desired position, the environment is separated into three zones. In the Ballistic Zone, the speed of the robot is set at its maximum. When the robot is in the Controlled Zone, it should decrease the speed. And the speed will be zero in Dead Zone. Based on the comprehensive implementation of all the behaviors and motion control, the formation could reach the target at last. Practices have shown this strategy has strong flexibility and practicality [7, 8].

At the level of behaviors, dynamical systems theory is used as a theoretical language and tool to design a distributed control architecture that generates navigation in formation, integrated with obstacle avoidance, for a team of three autonomous robots [9]. In [10], the number of basic behaviors increases to five and a series of generation functions to generate control parameters for behaviors' combination are designed to perform formation control tasks in unknown environments.

The advantages of behavior-based approach are its relative simplicity, explicit feedback and availability in obstacle avoidance. The shortcoming is the lack of a clear definition of group behaviors, which makes it difficult to analyze the local control rules with mathematical methods. Given these realities, this approach is often associated with other formation control methods [11–13].

2.3. *Artificial potential field techniques*

The approach based on artificial potential field concept was presented by Khatib [14]. The basic idea of this approach is the vehicles move in a field of forces which is similar to the electric field generated by the positive and negative charges. The position to be reached is an attractive charge and obstacles are repulsive charges, as shown in Fig. 3. Obstacles produce repulsive forces on the vehicle while the target pulling on it so that the vehicle could move along the gradient direction of the potential field.

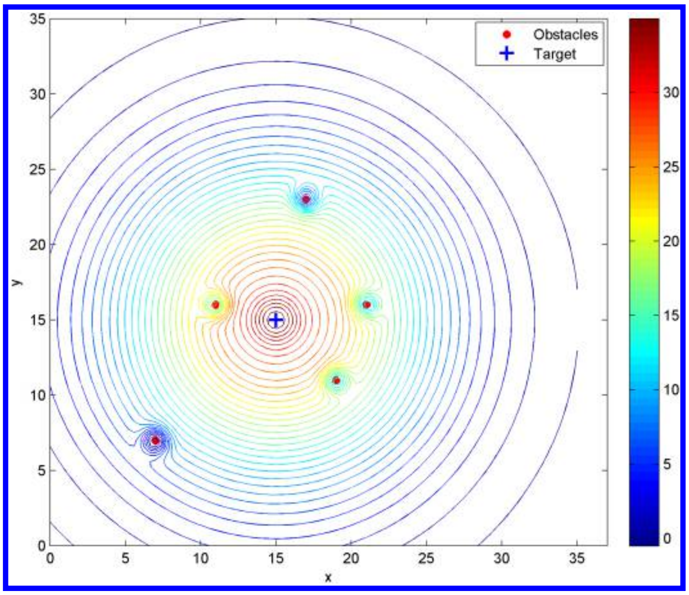

Fig. 3. Artificial potential field.

The primitive artificial potential field method for formation control is applied to the static 2D plane. In the study presented in [15], specific artificial potential fields for each robot relative to the other robots are calculated to produce stable formations in equilibrium with obstacles avoidance. Confronted with the environmental complexities, a novel approach for representing formation structures in terms of queues and formation vertices is introduced in [16], as well as the new concept of artificial potential trenches, for effectively controlling the formation of a group of robots. This scheme improves the scalability and flexibility of robot formations when the team size changes, and at the same time, allows formations to adapt to obstacles.

Artificial potential field approach can also be combined with other control methods and carried out in 3D environment. A solution using 3D potential field for collision and obstacle free formation flight and reconfiguration of groups of autonomous helicopters is presented in [17]. The solution is based on potential fields using a virtual leader and taking the vehicle's velocities into account. Also some novel methods are presented to generate the potential field used in the formation control [18, 19].

The advantage of the artificial potential field method is that the definition is explicit, and it is suitable for real-time control, especially for the collision avoidance problem in the environment with obstacles; the deficiency is the design of potential field functions is sometimes difficult and the problem of local minimum should be taken into consideration [20].

2.4. *Leader–follower schemes*

In the leader–follower approach, the basic idea is that the leader tracks predefined referenced trajectory, and the followers track transformed versions of the states of the leaders according to predefined schemes. The leader–follower-based formation control is applied to multiple mobile vehicles depending on relative orientations or distances [21]. Given the position a leader vehicle, the reference trajectory for the follower is set such that its position is shifted by a distance *d* relative to the leader as shown in Fig. 4. The reference trajectory of the follower is generated as the leader cruises and a virtual vehicle is designed to track the reference trajectory. Next, the position tracking control is formulated for the follower to track the virtual vehicle trajectory.

Besides the typical leader–follower method, Shao *et al.* [22] develops a hierarchical top-down control architecture which combines the advantages of the leader–follower approach, distributed control and graph theory. What is more, on the basis of the dynamic model of vehicle, feedback linearization is realized more effectively. Nevertheless, it is sometimes too complicated to give a complete model for the controlled object. Cui *et al.* [23] develop an approximation-based control technique to handle the model parametric uncertainties and unknown disturbances for the follower. The residual error between vehicles within the formation is proven to converge to abounded compact set and control performance is guaranteed by suitably choosing the design parameters. But the follower's trajectory is predetermined without the need for leader's velocity and dynamics due to weak underwater communication and low bandwidth. Since the robots' velocities are constrained, Dai and Lee *et al.* [24] give a geometrical waypoint method so that the follower robots move to their desired waypoints effectively. In the situation that robots' control inputs are forced to satisfy suitable constraints that restrict the set of leader possible paths and admissible positions of the follower with respect to the leader, a peculiar strategy is proposed that the follower position is not rigidly fixed with respect to the leader

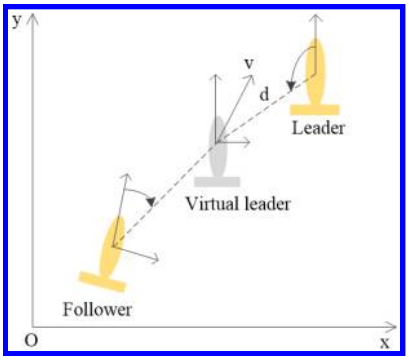

Fig. 4. Illustration of leader and follower positions.

but varies in proper circle arcs centered in the leader reference frame [25]. Despite the widespread use of this approach, all the methods mentioned above neglect the situation when robots move backwards in the leader–follower formation. To solve this problem, Chen *et al.* [26] propose a separation-bearing-orientation scheme (SBOS) for two-robot formations and separation-separation-orientation scheme (SSOS) for three-robot formations. Unlike the other leader–follower approaches, the orientation deviations between the leaders and followers are explicitly controlled, which successfully solve formation controls when robots move backwards.

In conclusion, the greatest advantage of the leader–follower approach is that it is easy to understand and implement, since the coordinated team members only need to maneuver according to the leader. However, there is no explicit feedback from the followers to the leader, and the failure of the leader leads to the failure of the whole formation team.

3. Main Technical Problems in Underwater Formation Control

In recent years, underwater formation control is investigated for multi-AUV system. Some approaches for aerial flight formation control and ground mobile robot formation control are already applied to multi-AUV system. However, the characteristics of multi-AUV system are so different from the air and ground robot systems that the formation control methods for multi-AUV system may not be categorized into the four existing techniques mentioned above. Therefore, this section focuses on the critical technical problems which multi-AUV underwater formation control is encountering and analyzes the corresponding solving skills.

3.1. *Problem of AUV's dynamic complexity*

The multi-AUV system is often treated as a nonlinear dynamic system which has so many parameters to be determined that the controller's design is very difficult according to some papers [27, 28]. The mathematical model of a single AUV in six degrees of freedom is considered complicated. Given that some parameters cannot be accurately measured or cannot be determined due to the technological constraints, a simplified model, which is underactuated or nonholonomic, is usually adopted for multi-AUV system in the existing literatures [5, 24, 25]. In [23], a new control method based on approximation is presented to handle the uncertainty problem of the AUV model. Function approximators are employed to compensate the unknown items in the control. Moreover, in order to deal with the nonlinear formation keeping and mooring control of multiple non-holonomic AUVs, a smooth feedback control law for the formation-keeping is presented by taking advantage of the Lyapunov direct method in [29].

On the contrary, some papers adopt decoupled control method to handle the dynamic complexity without simplifying the dynamic model. For example, Yang *et al.* [30] introduces a decoupled design procedure, so that formation controllers designed for particle dynamics can be generalized to formation controllers for fully actuated AUVs with six degrees of freedom dynamic models for motions in 3D space. The orientation control and the translation control are first decoupled following a standard inner–outer loop approach. Then a geometric approach is followed to separate the translation dynamics into formation shape dynamics and formation center dynamics.

The two kinds of approaches both have their advantages and disadvantages. Whether to choose the approximated model or choose decouple the dynamics depends on the working conditions and the client's requirements. Although the above literatures solve the dynamic problem to a certain extent, these methods mainly simplify the mathematic models and the complexity of dynamic system is not solved thoroughly. There is not yet a unified dynamic model to apply on the underwater multi-AUV system and the dynamics of single AUV is sometimes too difficult to describe.

3.2. *Problem of environmental complexity*

The environmental complexity of multi-AUV underwater formation control, mainly include two aspects: the problem of obstacles and the problem of current disturbance. In the working environment with many uncertainties, the AUVs are inevitable to encounter obstacles. Unfortunately, the movement control of AUV formation varies greatly from the air or ground formation, which leads to searching of new suitable obstacle avoidance strategies for multi-AUV system. Meanwhile, the underwater environment is complex and changeable. AUVs are inevitably under the influence of the ocean current which causes various disturbances. Reasonable and effective anti-current strategies are needed urgently.

Although there are tremendous researches on obstacles avoidance for air and ground vehicles, few studies has been done according to existing literature. As for the ground mobile robot formations, some scholars adopt behavior-based obstacle avoidance approach [12, 13], and some use potential field method to achieve the same goal [19]. In [31], a synthesized approach of the preceding two methods is presented: based on the behavioral structure, when a mobile robot gets close to an obstacle while moving toward its target, a rotational potential field is applied to lead the mobile robot to avoid the obstacle, without locating in local minimum positions.

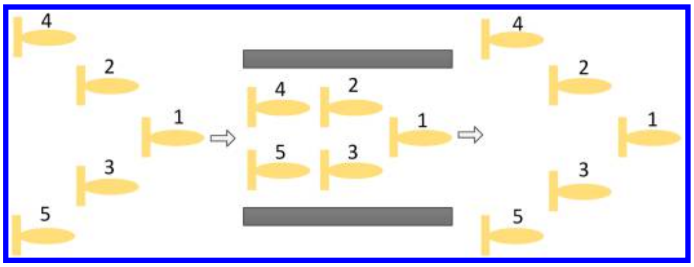

Fig. 5. Formation transform of multi-AUV system.

In all the literatures above, the obstacles are treated as geometric point. Position relationship-based obstacle avoidance algorithm was designed to detour along the edges of obstacles in [32]. Virtual potential point-based formation keeping algorithm was employed by incorporating dynamic strategies which were decided by the current states of the formation. Simulation results show that an optimal path can be dynamically planned with fewer path nodes and smaller fitness, even with a concave obstacle.

Another situation is that the formation can change its structure in a narrow area and restore back after passing, which is common in real-world environment [33]. For instance, the AUV formation team need to pass through a narrow strip of water, the formation of size and shape are changed to ensure the team to get through, and then restored to the original formation, as shown in Fig. 5.

Considering the ocean current influence, Hou and Allen [34] create simulation scenarios in which a team of vehicles cooperate to track a target in a water current environment. This paper customizes several behavior-based rules to satisfy the requirement of the desired scenarios. Fuzzy logic controllers are used to set different priority weights for each rule on-line according to the situation that the vehicles meet and the guidance law is modified as the navigation rule in a water flow environment.

Unfortunately, underwater environment is extremely complex. Situations mentioned above are mostly set manually and are different from real-world condition, so that many methods are still stagnating on theoretical stage.

3.3. *Problem of severe underwater communication constraints*

Given that the underwater formation of multiple AUVs requires internal communication ability to exchange information, such as velocity and position messages between the team members, the problem of severe underwater communication constraints become a research focus in recent years. Nowadays the communication between underwater vehicles is mainly based on the underwater acoustic system. However, the speed of sound in the water is slower than electromagnetic wave while the noise level is very high.

What is more, the underwater environment is complex with disturbance sources such as turbulence, rocks, underwater creatures, etc. All of these inevitably cause delays and multipath phenomenon. Communication range and bandwidth limitations form a barrier to large scale formation control applications.

To solve this problem, Ren and Sorensen [35] proposes a unified, distributed formation control architecture that accommodates an arbitrary number of group leaders and arbitrary information flow among vehicles. This architecture requires only local neighbor-to-neighbor information exchange, so that bandwidth limitations for the group can be handled in limiting the amount of group trajectory information availability within the group. The deficiency of this strategy is some information including the velocity is neglected except the position message.

One way to treat this difficulty is to design a controller which relies on the information transmission as little as possible. In [36], the authors provide an overall design for AUVs that achieve formation control by a separation between formation tracking (in space) and inter-vehicle coordination (in time), which makes these two tasks essentially decoupled. Passivity-based techniques and consensus tracking theories are brought together to yield a distributed control strategy, by which the problems existing in current literature that a common reference velocity signal being available to all cooperating vehicles are explicitly extended.

On the other hand, Cao *et al.* [37] propose a distributed containment control algorithm under a fixed network topology where the communication patterns among the followers are undirected and derive conditions on the network topology. In this case, the velocity measurements of the followers and the estimation of the leader's velocity are not required. Although some signals could be omitted by certain control algorithm, this method may not be practical, because the formations are assumed to be unchanged in the whole procedure which is impossible in the real environment, and it could not handle the situation when the communication is totally down.

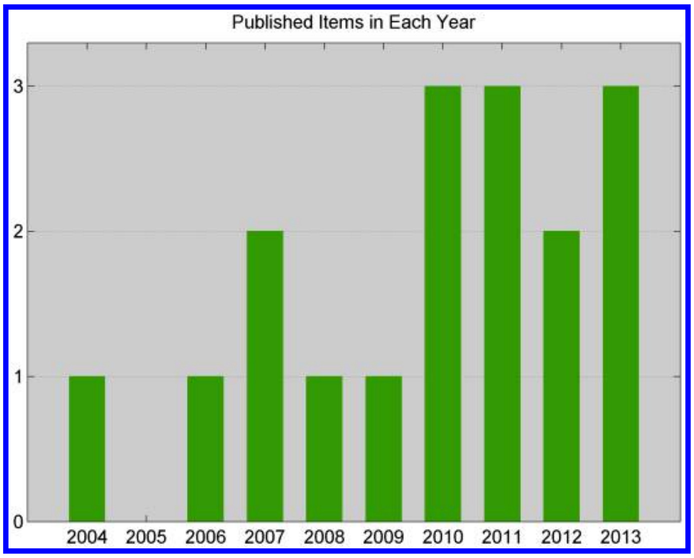

Fig. 6. Published items since 2004.

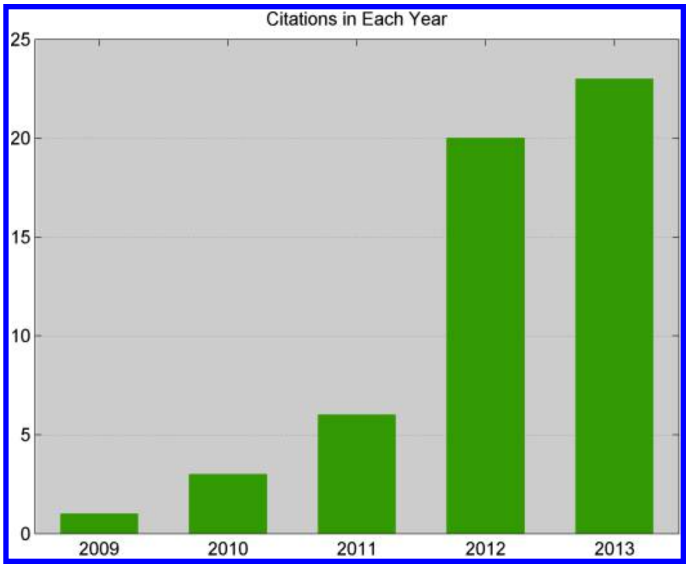

Fig. 7. Citations since 2009.

4. Published Items in this Field in Recent 10 Years

The research on formation control of AUV starts relatively late and the literatures are much fewer than those on mobile robots and aerocrafts. According to the search results of Web of Science, there are totally 17 papers published in recent 10 years (2004–2013), and citations to these papers have appeared since 2009. Published items in each year and citations in each year are shown in Figs. 6 and 7 separately. These research results are cited 53 times in sum till 2013. As the graphs illustrate, the research interest in this field is growing year by year despite the small number of papers published.

5. For Future Study

As mentioned above, many achievements have been made on the research of formation control. However, most of the existing results are based on pure theoretical research without sufficient experiments and practices. Compared with aeral vehicles formation or ground mobile robots formation, multi-AUV formation control studies are lagging behind, which is mainly caused by the complexity of underwater environment. To solve the three critical problems discussed in part three, there is a need for further in-depth studies of the formation control methods for multi-AUV system:

(i) Robustness of a controller is very important to the whole system. As the control strategy for multi-AUV system is much more complicated than the control of a single robot, the desired robustness is hard to achieve. In recent years, distributed controller for multi-vehicle system is becoming more and more popular [38, 39]. Some papers already considered the stability of multi-agents systems using the Lyapunov-like function for convergence analysis to support the proposed scheme [40]. With the increasing scale of the controlled system, robustness design of the distributed controller for multi-AUV system is challenging and will become a focus of the future study.

(ii) As discussed above, the actual application of multi-AUV formation underwater is the purpose of all the studies. In the previous literature, single robot is often referred as a particle, and simulation experiments are conducted in a 2D plane, which is far from practice. Therefore, analysis of formation control in 3D space is urgent, with the consideration of obstacles, ocean current and communication constrains. Ge *et al.* [41] give us some formation control simulations in 3D environment and a solution when communications are limited to the particle-like multi-agent system. But the underwater activities of AUVs with the kinematics model of six degrees of freedom, includes more uncertainties than other kinds of vehicles, so that it is necessary to establish a generalized 3D model with strong fault tolerance to handle uncertainty and constraints.

(iii) In the development of formation control, design of innovative control algorithms is the eternal theme and kernel of the study. On one hand, the integrative formation control approaches make up for the drawbacks of the existing algorithms by integrating some related methods together to present new characteristics. For example, the combination of behavior-based method and leader–follower method; distributed controller including several approaches; hybrid formation control method proposed in [42], etc. On the other hand, new control theories are proposed, such as the artificial intelligence-based methods which handle the cooperation problems of multi-robots in unknown and dynamic environments [43, 44], and the mathematics-based formation control technology [45, 46], which are important to the future study in this field. Additionally, design of novel controllers based on artificial intelligence combined with the development of modern control theory and technology, should become another important aspect of formation control for multi-AUV system.

6. Conclusion

There is no doubt that the study on formation control of multi-AUV system has made great progress. But there are still some important limitations and problems to be further explored. This thesis makes a conclusion of the major issues in related researches. On the basis of previous literatures, formation control methods are summarized as four categories first. Second, the peculiarities and difficulties of formation control for multi-AUV system are analyzed and the critical technical problems are summarized into three aspects, where both the advantages and drawbacks of the corresponding solutions are commented. Finally, the valuable development trends of formation control are discussed.

Acknowledgments

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