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A Survey of Multi-Agent Systems on Distributed Formation Control

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Multi-agent formation control is an important part of distributed perception and cooperation, which is convenient to complete various complex tasks and would be a key research direction in the future. This paper reviews the corresponding problems of formation control and the existing centralized and distributed formation control strategies. In particular, we discuss four types of distributed formation control methods based on position and displacement in the global coordinate system and distance and bearing in the nonglobal coordinate system, respectively. Moreover, this paper analyzes affine formation which does not require the global coordinate system. Combined with the current practical applications of multi-agent systems, the latest research for the formation control of the unmanned aerial vehicle (UAV), unmanned ground vehicle (UGV), unmanned surface vehicle (USV) and autonomous underwater vehicle (AUV) is given. Finally, the challenges and opportunities in this burgeoning field are discussed.

Keywords: Multi-agent systems; distributed control; formation control; formation application.

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1. Introduction

Usually, a single agent does not have the ability to perform distributed complex tasks [1, 2], and it is difficult and costly to carry out desired development. Facing complex applicational scenarios, a single agent is powerless to achieve the design objectives. Nowadays, technology is becoming more mature since the types of agents are becoming more abundant. As a result, the number of agents facing various task requirements is increasing. At this stage, the structure of a single agent becomes more and more complex, the perception and positioning accuracy increases, while the motion planning algorithm becomes more efficient using more precise control effects. Meanwhile, a multi-agent system emerges accordingly [3–6].

Multi-agent systems adopt distributed control regarding both space and time, so they are more suitable for practical complex tasks to improve the performance, reconfigurability and flexibility of the system structure, reduce costs, shorten task time and collect more extensive data, ensure ideal results with more reliable data and increase the probability of task success. In addition, with the help of

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multiple simple and low-cost agent monomers, it is possible to build multiple agents that can adapt to highly complex tasks. Compared with complex single-agent systems design, multi-agent systems have lower R&D costs. Therefore, a multi-agent system has significant advantages at the application level.

In 2005, the report, "UAV System Roadmap 2005–2030", pointed out that "fully autonomous swarms" are the highest level of UAV autonomous control [7]; in 2017, "National Robotics Plan 2.0: Nowhere Collaborative Robots in the Absence", highlighted the scalability and connectivity of robots, e.g. how the robots distribute perception, planning, action and learning in uncertain environments and how to improve safety, robustness and reliability in complex environments. In 2018, a review article published in "Science: Robotics" listed multi-robot systems as a key development direction in the next decade, and it is also one of the ten challenges in robotics [8]. All these statements demonstrate the importance of multi-agent systems.

Multi-agents usually run information to improve the perception ability of the system and facilitate cooperation for complex tasks. The idea of controlling multi-agents to operate in formations is inspired by fish foraging, birds flocking and ant migration [9] shown in Fig. 1. Through the research on such biological activities, it has been noticed that the operation efficiency of the group can be effectively improved by a specific formation activity. Thus, many researchers apply formation operation to robot systems for aerospace [10], transportation [11], environmental detection [12] and others.

The main contribution of this paper is to review the benefits and drawbacks of common group control schemes from the standpoint of centralized and distributed structure, as well as to summarize four commonly used distributed control strategies from the structure, difference and research status of distributed control strategies. Meanwhile, the affine formation control strategies based on stress matrix in high-dimensional systems are emphatically introduced. In the aspect of application, this paper presents the applications of formation control strategy in Unmanned Aerial Vehicles (UAVs), Unmanned Ground Vehicles (UGVs), Unmanned Surface Vehicles (USVs) and Autonomous Underwater Vehicles (AUVs) in recent years.

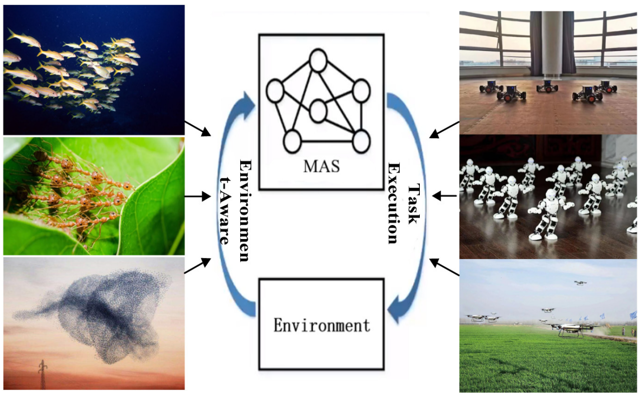

Fig. 1. Natural inspiration.

The remaining parts of this paper are organized as follows: In Sec. 2, the problem descriptions of formation control have been given. Then, Sec. 3 introduces the distributed formation control strategies. The research and development of affine formation control are reviewed in Sec. 4. Then, Sec. 5 summarizes the recent applications of formation control in various fields. Section 6 provides the perspectives and challenges based on the mentioned formation control methods and applications; finally, the full text is concluded in Sec. 7.

2. Formation Control Problems and Strategies

The formation control problem is divided into three subproblems [13]. The first one is formation generation, which drives the agents in random situations to form the desired formation topology. Second, the control strategy must ensure and maintain the desired formation shape, when the team acts. The third one is formation reconstruction. Note that the formation may encounter different types of situations in complex operational environments, such as encountering obstacles and interruption of connections between agents, so the interaction topology must be reestablished to adapt to the new conditions when the team encounters such aforementioned problems. For the problem of reconstructing interactive topology control, researchers propose two groups of control strategies, centralized and distributed.

For the centralized scheme, a ground receiving station or an agent core processing unit with strong computing power is usually required. The core unit monitors and coordinates team behaviors according to the global task based on the data from all remaining agents. All agents must remain connected to the core unit and the hierarchical structure is shown in Fig. 2.

For the distributed scheme, there is no core unit in the organization. Agents in a formation can communicate and share information with other members as shown in Fig. 3. Each agent can be the original processing unit, and can independently observe the environment for decision-making. Contrary to a centralized control scheme, the distributed control scheme has more robust communication and scalable system structures. For instance, the achievements on cooperative control of multi-agent systems were introduced, especially the cooperative control under various agent dynamics, communication transmission delay and

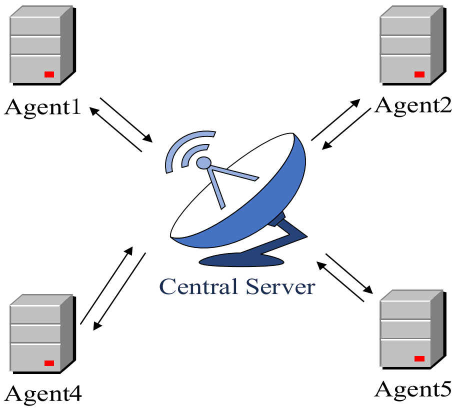

Fig. 2. Centralized strategy.

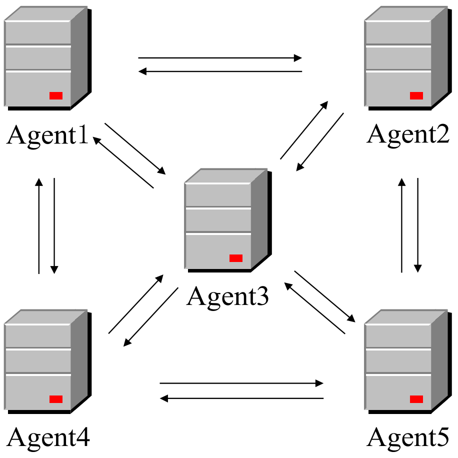

Fig. 3. Distributed strategy.

event triggering strategies. In terms of formation control, these achievements included the characteristics and types of circular formation control [14]. Meanwhile, the control design of circular formation with target circle and fixed center had also been extensively studied [15–18].

Formation control mostly relies on centralized communication in the past, in which agents share information directly or communicate via broadcast information. However, centralized communication has weak fault tolerance and reliability, while distributed communication exchanges information through the observation of the environment or other agents and does not depend on the future behavior of other members, so distributed systems are more competitive when centralized communication between agents are not available or reliable.

Table 1 briefly shows the comparison of the solving performance [19] of the two strategies. Firstly, the distributed scheme has better real-time performance. Because the calculation amount of the centralized scheme is concentrated in the central controller and the calculation is

Table 1. The performance comparison of the two strategies.

Performance	Real-time	Extensibility	Robustness	Optimality
Centralized	bad	bad	bad	good
Distributed	good	good	good	bad

complex, the scheme will be invalid if the communication condition is bad, while the distributed scheme exchanges information through the observation of the environment or other agents, which has strong real-time performance; Secondly, the distributed scheme has better scalability. The distributed scheme has more robust communication and extensible system structure, while the centralized scheme has weak scalability due to its own structural characteristics; thirdly, the distributed scheme is robust. Although the centralized scheme can consider the overall situation, it has some disadvantages such as poor robustness and huge waste of energy. Since the core unit is responsible for global decision-making, the failure of the core unit will lead to the failure of the entire formation. For each agent, the computing power of the body is not utilized, and the required connection links between the core unit and other members will also burden the communication resources. Contrary to centralized control schemes, distributed control schemes have more robust communication structures and they also perform well in obstacle avoidance and information consistency; fourthly, the centralized scheme can better obtain the global optimal solution (for instance, the minimum task cost, the most reasonable target ratio and the optimal motion trajectory, etc.) [20].

The control scheme can be divided into the following three categories [21–24].

(1) Based on leader–follower, all formation members are assigned two roles either as leader or follower.

By navigating along a predetermined or temporarily set route, the leader can grasp the movement trend of the entire formation, and then it follows the basis to achieve formation control. It has been shown that this formation control implementation is simple. For instance, some scholars have studied the swarm control problem of large-scale fixed wing UAVs in recent years [25].

(2) Based on virtual structure: First, the kinematics and dynamical characteristics of the required virtual structure are determined. Then, we deduce the corresponding characteristics of the virtual target point on the virtual structure, and finally, make the robot track the corresponding virtual target point by designing an appropriate formation control law. Some control algorithms based on virtual structure method were proposed for the control problem of multi-UAV and multi-robot formation [26, 27].

(3) Behavior-based approach: In this approach, several expected behaviors are specified for the agents. The

expected behaviors may include cohesion, collision avoidance, obstacle avoidance and so on. For instance, a multi-aircraft adaptive distributed formation flight strategy based on close-range behavior observation can solve the problem of poor flexibility of distributed formation [28]. Also, affine formation control strategies could achieve the expected targets.

3. Distributed Formation Control Method

According to [1], the majority of contemporary research on distributed formation control may be categorized into four groups: Position-based, displacement-based, distance-based and bearing-based. The global coordinates are necessary for position and displacement-based approaches, but not for the other two. The comparison of the four categories is shown in Table 2.

3.1. *Position-based formation control*

In position-based formation control [29, 30], agents actively manage themselves to advance toward a perceived absolute position in a global coordinate system. The desired formation can then be obtained. These formations are described in terms of the positions needed to complete the assignment. In essence, position-based control can produce perfect formations in the absence of perturbations, which means that agents may not even need to interact.

The position-based formation control is based on the intuitive agent model. It is more extensive than the control based on displacement, distance, and bearing because the agent needs more sophisticated perception tools, such as a global locator or a GPS. For actual formation control applications, it can offer a viable and practical option.

There are two research trajectories in the position control literature. To increase the adaptability and robustness of formation control, the interaction between agents is first incorporated [31]. Second, a centralized controller is created to collect feedback from the agents and the controller gives the agents the proper coordination directives (also known as virtual structures) [24]. Feedback synchronization is required, particularly when the agent's capacity to drive is impaired or limited. Although a single agent can essentially regulate its location to construct the appropriate absolute position assignments, interactions between agents can improve the precision of the formation performance [32].

3.2. *Displacement-based formation control*

The displacement-based formation control is an extension of the position-based formation control, where the parallel movement of the agent is taken into account, see Fig. 4.

In displacement-based control [33–35], agents are presupposed to be aware of their neighbors' relative locations in relation to a global coordinate system. Agents can actively manipulate displacements and generate the desired formation with the predicted displacement value. The majority of agents are thought to be unable to sense their absolute location in relation to the global coordinate system. Therefore, interactive topologies' linkages and interactions are also necessary.

Displacement-based formation control can guarantee quasi-global asymptotic stability while requiring communication between adjacent agents. Compared with gradient-based control laws, it has obvious advantages in achieving quasi-global stability, although in-phase communication among neighboring agents is normally considered as a disadvantage.

The existing literature for displacement-based formation mainly focuses on heterogeneous agent dynamics [36–38] and connection preservation and conflict avoidance [39–41].

Table 2. Features of formation control based on position, displacement, distance and bearing.

	Position-based	Displacement-based	Distance-based	Bearing-based
Sensed variables	The absolute position of the agents	The position of neighboring agents	The position of neighboring agents	Align the bearing vector in the coordinate system
Controlled variables	The absolute position of the agent	The position of neighboring agents	The distance between interacting agents	Align the bearing vector in the coordinate system
Coordinate systems	Global coordinate	Global coordinate	Local coordinate	Local coordinate
Interaction topology	Generally not required	Connectedness or existence of a spanning tree	Rigid or persistence	Rigid or persistence

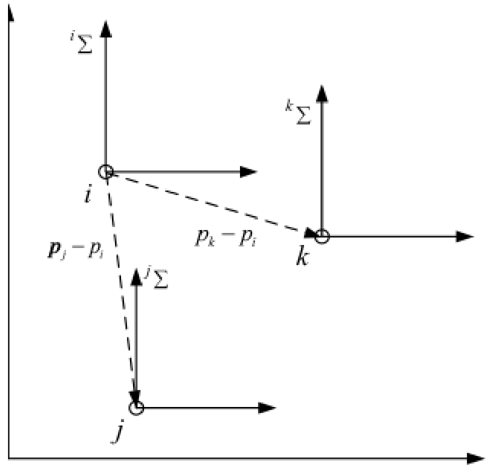

Fig. 4. Displacement-based control [1].

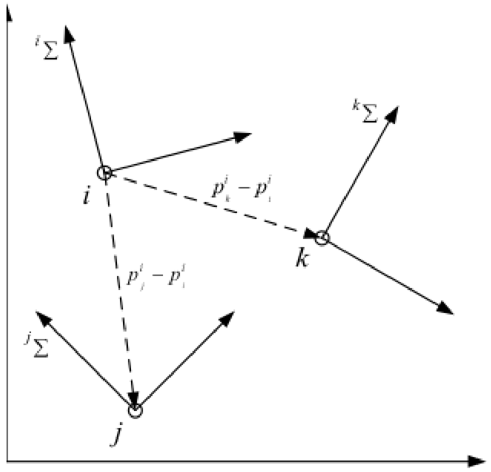

Fig. 5. Distance-based control [l].

3.3. *Distance-based formation control*

As shown in Fig. 5, the distance-based formation control adds the rotation of the agent based on the displacement-based formation control. The explored nonlinear model may be more complex than the position- and displacement-based control laws since the distance-based control law does not employ the global coordinate system.

Each agent senses the relative location or distance of nearby agents relative to the local coordinate system without a shared sense of direction in distance-based formation control [42–44]. To accomplish their ideal formation, which is determined by the desired distance value between any pair of agents, they actively manage the distance between agents. The interaction graph of the agents must be stiff or durable since only the distance between them is actively managed in distance-based control [45].

In distance-based formation control, the most intuitive method is the gradient-based method [46]. The gradient-based formation control law uses a potential function to generate a local controller for distributed agents. If the potential function can achieve predefined distances, it can be considered that the desired formation is achieved.

It is crucial to select a suitable potential function because the gradient of the potential function must direct the distributed formation controller. The gradient control law can often be realized in two ways. The first strategy is to provide globally stable beginning conditions for a specific graph. The generic rigid topology is where the second strategy falls. When the topology is expanded to include generic n agents, local stability can be ensured. Since the gradient control law is in use, it is difficult to stabilize the formation from any given initial condition to the desired formation. As a result, a particular type of global stability is taken into account in practically all current studies.

A distributed control law was proposed to achieve 2D triangular formation [47], which can make any initial non-collinear, positive (and negative) triangles rapidly exponentially converge to the desired positive (and negative) triangles. It also shows that there is an unstable set of initial collinear formations that remain collinear and may change with $t \to \infty$.

Also, a brand-new formation control method based on agent separation was put forward [48]. The researchers constructed a control law using distance dynamics to directly regulate the separation between agents. For infinitesimal stiff formation, the control rule achieves local asymptotic stability. The triangular infinitesimal rigid formation is globally asymptotically stable under the suggested control rule, and all distance squared errors exponentially and monotonically approach zero. The stability analysis demonstrates that, as an extension of the previous findings, any control rule connected to the gradient law of positive matrix multiplication may provide the local asymptotic stability for infinitesimal stiff formations.

It was investigated how inter-agent distance control affected the local asymptotic stability of undirected formations of single-integral and double-integral model agents [49]. First, it is shown that the gradient control rule may be used to create the undirected production of agents in n dimensions with single-integrator dynamics. The analysis demonstrates that the formation's infinitesimal stiffness is not necessary for local asymptotic stability, and it also demonstrated that agents with double integrator dynamics can achieve local asymptotic stability of an n-dimensional undirected formation under a gradient-like control law based on the topological equivalence of the dissipative Hamiltonian system and the gradient system. Additionally, the formation was expanded using a leader–follower configuration [50].

3.4. *Bearing-based formation control*

Compared with distance-based control, bearing-based formation control subtended angle and bearing vector, so that the formation can be scaled proportionally. The subtended angle and bearing vector are shown in Fig. 6.

In the bearing-based formation control problem, a group of agents (mobile robots, UAVs, etc.) must achieve a target formation specified by some azimuth information (bearing vector and/or subtended angle). One of the key points of bearing-based formation control is to use only orientation information to design the distribution control law.

For instance, a control rule based on sub-angles for triangular structures was established [51]. The triangular formations were regulated by monitoring the bearing angle to accomplish the necessary sub-angles and restrictions under the situation of orientation deviation was also achieved [52]. Some scholars introduced the notions of weak stiffness and infinitesimal weak stiffness and converted the distance constraints into sub-angle constraints [53]. It was also proposed to use distance-based stiffness to study formation stiffness under neighboring angular limitations [54]. According to the notion of infinitesimal weak stiffness and weak stiffness without incident edges, the formation control of triangular media was created, and the formation control of three-dimensional space was further investigated [55]. In addition, distance constraints and bearing constraints can also be combined to obtain enhanced formation control performance [56].

A bearing-based control law using the formation of acyclic persistent graphs was introduced [57], which applied to acyclic persistent graphs when the local coordinate system of the agent coincides with the public coordinate system. Additionally, a control rule that rotates the target formation by changing the leader's orientation was presented for the unaligned agents [58].

In order to realize the desired queue globally in finite time and estimate the upper bound of convergence time, two finite-time pure azimuth control laws were proposed [59]. Although the control laws required a longer stabilization time than [45], they may be more realistic in implementation. Subsequently, still from the perspective of finite convergence time, a new bearing-only formation control law with pre-specified convergence time was proposed [60], which achieved target formations in finite time. Also, the convergence time can be arbitrarily adjusted by users, and the derivative of the control input was continuous. Sufficient conditions were also provided to ensure almost global convergence and collision avoidance between the agents. In particular, the control law achieved global convergence with a "leader–follower" structure. Meanwhile, a bearing-only formation control law was proposed to track moving target formation and processing multiple agent models, which was suitable for the single integrator, double integrator, and unicycle models [61]. Meanwhile, a standard Lyapunov method was proposed to analyze the stability of the control law.

4. Affine Formation Control Strategy

Although the four basic formation control strategies, described in Sec. 3, have formed a consensus in the industry, these strategies achieve the target formation by constant constraints on the distance, displacement and bearing among agents, which affects the flexibility of the formation and makes it difficult to achieve affine transformation operations such as translation, rotation or scaling at the same time. To solve this problem, affine formation control strategies have been widely studied in recent years. An illustration of rotation, scaling and shear of a nominal configuration of a two-dimensional structure is shown in Fig. 7.

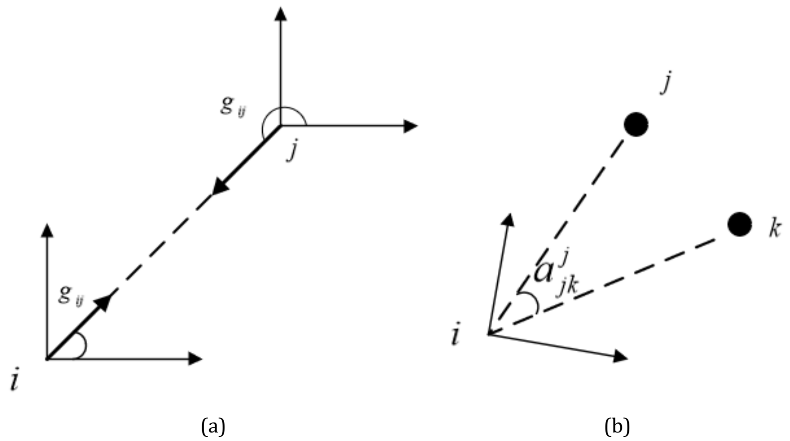

Fig. 6. Bearing vector and subtended angle.

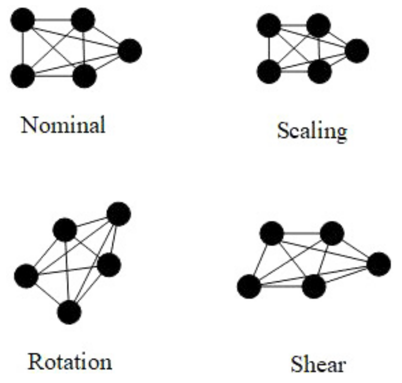

Fig. 7. Illustration of affine transformations.

4.1. *Stress matrix and formation control*

Most of the control laws were based on the real number domain in the early years, which was only suitable to describe one-dimensional dynamic equations. The subsequent research about the formation of multi-agent systems gradually expanded from the real domain to the complex domain. Compared with the real domain, the controller designed in the complex domain was more suitable for describing the kinematics equations in the two-dimensional plane. In order to implement translation, rotation and scaling simultaneously, a complex Laplacian strategy was first proposed [62, 63]. However, with the development of technology, a new problem arose on whether the methods that are applicable to higher dimensional systems are needed. Further research showed that the strategy based on stress matrix was promising to achieve formation control in higher dimensional systems. The stress matrix had similar properties to the Laplacian matrix, but the weights of the stress matrix could be positive, negative, or zero. Rigidity plays an important role in formation control based on the stress matrix and the uniqueness of a formation in the whole space was guaranteed by its 'global rigidity'. In addition, 'universal rigidity' was needed to ensure the uniqueness of the framework across all dimensions. The study of the multi-agent coordination problem mainly focused on the case with specific global and universal stiffness under the framework of generic configuration [64], where the construction of the stress matrix was also based on this premise.

4.2. *Affine formation control strategy based on stress matrix*

An advantage of the stress matrix is that it remains unchanged for any affine transformation of the formation configuration. Based on the stress matrix, an affine formation control method [66] was proposed, which simultaneously achieved two objective tasks: Keeping the agents in a specific geometry and implementing the actions required during the execution of the task. It was suitable for real-time continuous communication or sensing between agents. The proposed control law relied on the stress matrix, which could track time-varying target formation that is an affine transformation of the nominal configuration. The required formation maneuvers were only known to a few leaders, and the remaining followers only needed to follow the leader. The proposed control law was globally stable, and it did not require a global reference frame if the measurements could be obtained in the local reference frame of each agent [65]. The proposed control strategy solved the affine formation control problem based on the preamble dynamics or dual integrator agent dynamics model.

The control problem based on the stress matrices for agents with signal-integrator dynamics was studied, and the following conclusion was proved: An affine construction was stabilizable on the undirected graph if and only if the undirected graph was universally rigid, while an affine construction was stabilizable on the digraph in d-dimensional space if and only if the digraph was (d+1)-rooted [66]. Subsequently, the problem of scaling control for multi-agent systems was studied [67]. A new class of distributed control laws was designed by using stress and orthogonal projection, which only needed a pair of agents to share the scale information and could realize the scale transformation of the whole formation in high- dimensional space. It had also been shown that the equilibrium of the closed-loop system was limited only by the translation and scaling of the given configuration in all possible affine transformations if the corresponding stress matrices allowed a generic universally rigid framework.

Since triple integrator dynamics is widely used in robot control and flight control, the affine formation algorithm based on triple integrator dynamics and its implementation techniques are immediately proposed [68, 69]. Under the two assumptions, we found the following: (1) The framework is generically universally rigid; (2) the d+1 leaders are selected to span R^d space affinely. Two new control laws were proposed for continuous communication and periodic communication, respectively, which can track the nominal form of any time-varying affine transformation. In the continuous communication mode, the proposed control law could ensure that the error of the follower's position converges to zero if the leader's jerk is constantly zero and the control gain is selected according to the given inequality; In the periodic communication mode, each agent has continuous-time dynamics but communicates with neighbors at discrete instances. If the jerk of the leader is zero, and the control gain and period are selected properly according to the given two inequalities, the proposed control law could keep the tracking error stable at the origin. The above theory gives sufficient conditions to ensure the global stability of the control law and the proposed algorithm has been applied and implemented in different simulation experimental scenarios for affine formation control of multi-agent systems described by triple integrator dynamics. The agents could achieve affine transformation of formation as long as the leader knew the information of the formation maneuver.

In addition, affine formation control problem of general linear multi-agent systems over undirected graph in the presence of time delays is studied [70]. A predictive observer is designed for the tracker to predict the future state under different delay conditions, and the affine formation control law, which could be implemented without using global information, is designed according to the predicted state.

5. Application of Formation Control

In recent years, multi-agent system formation control has become widely employed in the civil and infrastructure sectors, particularly in harsh or inhospitable locations. Multi-agent technology issues may be loosely split into two groups [71]. On the one hand, it primarily concentrates on area coverage, aggregation, mapping, migration and self-organizing grid. On the other hand, it supports entity objects that are based on the environment, including target search, odor source recognition, ore vein finding, foraging, and disaster relief.

Unmanned vehicles [72], which may be further broken down into UAV, UGV, USV and AUV, are the primary carriers of formation control applications. The next section examines the applications in these four directions.

5.1. *Application in UAV*

UAVs, known as drones, may be flown independently or remotely and are capable of carrying payloads. UAVs are frequently employed for traffic monitoring, agricultural sowing, irrigation and aerial photography [73].

As the representative studies, Juan *et al.*'s [74] investigation of the distributed leader–wingman formation control problem for quadrotor UAVs served. Each quadrotor UAV has an inbuilt digital processor that calculates its control signals, and to accomplish dispersed formation control, a wireless communication channel was constructed between the leader and the wingman. To address the formation control of quadrotor UAVs, Rinaldi *et al.* [75] suggested a linear quadratic control approach. Robust control was employed by Renan *et al.* [76] to address the UAV tight formation control issue. A fuzzy control-based quadrotor UAV formation control solution was put out by Abbas *et al.* [77]. To accomplish the desired formation for the two-dimensional plane formation, the logic controller's settings are tuned. To solve the issue of UAV formation maintenance and transformation utilizing sliding-mode controllers, Li *et al.* [78] separated the UAV model into three channels. It has looked at the designs and implementation of UAV formation maintenance and reconstruction.

5.2. *Application in UGV*

UGVs are utilized to complete tasks including rescue, encirclement, cooperative handling and local searches in complicated and dynamic situations.

The key to steady driving of the complete chain vehicle system without accident is the speed of the UGV following the target vehicle steadily and swiftly. When regulating the entire system, more complicated elements must be taken into account because of the parameter uncertainties of the vehicle model and the nonlinear disruption of the external environment. A complicated vehicle kinematics model [79] was created with an adaptive approach. The chain formation control issue, in which the system employs a constant-spacing car-following strategy under the requirement of zero initial steady-state error, is resolved by estimating numerous unknown system parameters. The chain stability of the system under a zero initial steady-state error is analyzed using the particle model, and the control law is then created to implement the unmanned vehicle using a constant headway time-following approach [80, 81]. Using adaptive fuzzy logic to modify the system's SMC adaptive gain, Bamieh *et al.* [82] suggested a control technique that combined PI sliding-mode and backstepping to address the system's parametric and nonparametric uncertainty issues. Additionally, it demonstrated the superiority and efficacy of the suggested control mechanism. The flexible and robust time-varying formation tracking problem of UGVs under UAV guidance is studied [83]. Based on leader–follower method, a nonlinear controller is proposed to ensure the formation of free formation to control UGV, and a robust cascade speed/torque controller based on kinematic and dynamic models is proposed for TVF tracking tasks.

5.3. *Application in USV*

Due to their low price, great efficiency and extensive coverage, USVs are also appreciated in engineering projects. The investigation of undersea resources, removal of water pollution, disaster relief, maritime surveillance and inspection, etc. have all seen extensive usage of several USVs [84].

It has the following representative works: Liu *et al.* [85] proposed a two-layer environmental control framework suitable for multi-USV systems, which was extensively validated by lake experiments. Yu and Fu [86] studied the formation problem of unmeasurable speed. Do [87] developed a ship formation control scheme with regular sea loads to achieve a collision-free synchronous motion-tracking task. With the help of a fuzzy estimator, Peng *et al.* [88] proposed a distributed constrained control law for guiding multiple autonomous USVs with a virtual leader moving along a parameterized path. He then studied a co-operative timetable with connectivity preservation and collision avoidance [89]. Wang *et al.* [90] proposed a new distributed consensus algorithm, which makes the control input of each agent only need the output information from its neighboring agents and reducing the communication pressure of high-order systems. Park and Yoo [91] studied distributed networked uncertain USVs connection reservation and collision avoidance formation tracking problems. Zheng *et al.* [92] developed a distributed predictive path following controller that senses the arrival time of multiple autonomous guided ships on the water.

5.4. *Application in AUV*

Formation control of AUV is more challenging than other automatic devices due to the uncertain and coupled dynamics of the system, environmental disturbances caused by fish schools or ocean currents and underwater communication [93]. Related studies have shown that 99% of the seabed is still untouched. Knowledge from unknown oceans is important. Revealing the secrets of deep-sea ecosystems can uncover new sources of medicine, food, energy and other products. Therefore, AUVs are widely used as a type of underwater exploration tool [94] which have received widespread attention.

To achieve formation control, AUVs need to exchange some key information with each other through wireless communication. There are three main communication technologies: Radio frequency communication, optical communication and acoustic communication. Due to the nature of the underwater environment, acoustic communication is the most widely used technology [95]. However, underwater acoustic communication still has many limitations in practice (high propagation delay, path loss, noise, Doppler effect, etc.) [96].

There are two downsides to the limited communication distance for AUV creation applications. First, the likelihood of a collision would rise if AUVs remained close to one another. Second, AUVs have poor anti-interference capabilities.

Additionally, there are some more thorough examinations of AUV formation [4, 97, 98], covering topics including positioning strategies, typical AUV navigation and communication for formation. In order to examine position, path planning and coordination in terms of space and time, the control coordination problem involves distinct communication in the specified communication topology. It was believed that all AUVs would be able to use cutting-edge sensory technologies to acquire comparable velocity and location signals.

In conclusion, multi-agent formation control has important applications in UAV, UGV, USV and AUV. UAV, UGV and USV can not only realize formation control in their own platform, but also form a large platform. Due to the different attributes, the data between different platforms are also different and they are specific to their own particularity. Therefore, how to achieve heterogeneous data communication between different platforms is a key issue. Data link communication can realize the communication and data sharing between sensors, vision systems and control systems of different platforms. Formation control between different platforms needs to solve the consistency problem of data link communication. The internal formation control of UAV, UGV and USV platforms is different due to the different internal perception and decision-making level of platforms, which will affect the accuracy, real-time and effectiveness of formation control. Therefore, data link communication is the main way of information exchange among UAV, UGV and USV systems, and it is an important capability for unmanned systems.

6. Challenges and Opportunities

The cooperative control of mobile robots is mostly based on the formation control of multi-agent systems. Although there is a wealth of research in the area of distributed formation control, many unresolved issues remain. The following are the key elements:

(1) Future research should focus on developing hybrid control techniques with high fitness while also taking into account the dynamics of diverse systems. For instance, the industry-standard PWM protocol efficiently reduces the agent's running workload without the need for extra analog-to-digital conversion. The permitted modulation times vary depending on the agent. A projection operator is introduced to the leader for collective aggregation in the distributed PWM protocol developed by designating one agent visiting a specific interval as the leader and other agents as followers[99]. As previously said, every approach has unique advantages and disadvantages. There isn't a universal technique that works for all sub-agents since multi-agent systems may have several subsystems. One of the potential paths for future study is a hybrid mechanism,

which may combine certain conventional approaches and produce a hybrid mechanism in accordance with particular job needs.

(2) The design of controller for heterogeneous systems is still a challenge. Multiple agents need to cooperate with each other in applications, and usually the motion models of multiple agents are different, that is, heterogeneous. Due to the characteristic difference, the current research results of isomorphic agent systems cannot be directly applied to heterogeneous systems. The basic requirement to solve the control problem is to satisfy the coordination of heterogeneous systems, then consider the study of heterogeneous multi-agent cooperative control methods and propose appropriate control strategies according to different formation control problems. In order for cooperative control strategies to succeed, it is necessary to address the definition and management of information shared by different members within the system in order to facilitate coordination between these agencies. The constraints on kinematics and dynamics of the agents are ignored if heterogeneous agents are modeled as rigid bodies or particles.

(3) The security of multi-agent systems is also a challenge. Due to the unreliability of network communication of multi-agent system, including communication fault, environment and sensor measurement range limitation, subsystem fault and communication fault (network fault) occur frequently, which will seriously affect the normal operation of multi-agent system. Collaborative fault-tolerant control for multi-agent systems has attracted extensive attention in recent years. For example, intermittent Denial of Service (DoS) attacks [100–103] are a common form of attack. It attacks the system defects to realize the normal system paralysis, unable to operate normally, how to design fault tolerant controller, control behavior can adapt to the changes of the external environment and internal organization to ensure that each subsystem to achieve synchronization conditions is the current difficulties and challenges.

(4) Applications of signal perception and transmission technology are significant, and they serve as a crucial link in the collaboration of multi-agent formations. In other words, there are unknown environmental dynamics, constrained perceptive capacities and diverse signals in the typical communication environment, which is harsh or less than optimal. The use of hardware may also result in a number of real-world issues. For instance, the dynamical properties of satellite orbits and difficult attitude coordination tasks show that their relationships are time-varying and interference will cause the uncertainties to alter. Relative state determination and shape-preserving control in the range of millimeter-level or even greater accuracy are required for particular activities, such as synthetic aperture photography and optical astronomical observations [104]. Therefore, multi-agent formation control under nonideal communication conditions is a challenge.

Deep learning and reinforcement learning have also been used in the construction of formation controllers as a result of the development of machine learning. It gives the agent the capacity to handle challenging issues and adjust to erratic situations with ambiguous barriers. Distributed control will function more efficiently in real-world applications with the addition of mobile leader agents that have autonomous learning capabilities.

7. Conclusion

Large-scale multi-agent systems' general control issue might be resolved through formation control. This survey covers the primary issues with state-of-the-art formation control methodologies by contrasting distributed and centralized control systems. Basically, the benefits of dispersed control techniques in large-scale formation have made it an emerging hotspot in recent years. The multi-agent distributed formation control approach with and without global coordinates based on position, displacement, distance and bearing is described in depth in Sec. 1 of this study, which deals with control methods. Less global information will have larger benefits for practical applications, such as those involving UAVs, UGVs, USVs and AUVs, from the perspective of complex settings and difficult communication situations. Finally, future research areas are explored together with the accompanying possibilities and difficulties. These directions include formation control structure, complex agent model and communication under hard settings.

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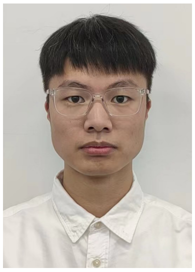

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