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The Survey Paper : Formation Control For Swarm Robots

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Abstract**—**This paper presents a survey on formation control of swarm robot. It focuses on the stability of swarm robots when they achieve the desired formation. This paper also discusses the stability of formation with three classifications formation control approaches and its application in a dynamic environment and unknown. This manuscript also summarizes problem formulations, discusses distinctions, and reviews recent results on the formation control schemes.

Index Terms—formation control, swarm robot, stability, dynamic environment and unknown

I. INTRODUCTION

SWARM robotics research is a field of research which studies how systems arranged by multiple autonomous robots can be used to accomplish collective tasks. Occasionally, these tasks can either be accomplished by each individual robot alone, or carried out more effectively by the robots as a group [1]. Collective task of swarm robots include aggregation, flocking, foraging, object clustering and sorting, navigation, path formation, deployment, collaborative manipulation and task allocation [2] .

In the last decades, the swarm robots have been used in various scopes of applications, including odor localization [3], mobile sensor networking [4], medical operations [5], surveillance and search-and-rescue [6]. The tasks of these applications are very complicated and difficult to be defined. To resolve complex tasks, the problem on how to control a group of robots in order to make them move as a group towards a common work is the most important and fundamental one.

According to the positions that the robots must occupy, the complex tasks in collective movement problems are classified into two categories, i.e. formation control and flocking [7]. The formation control or robot formations problem consists of how to coordinate a group of robots in maintaining a determined position while moving in the environment [8]. Sometimes, there are just the relative positions between robots are determined. On the other hand, flocking is the problem of moving a group of robots when the shape and relative positions between the robots are not important. In a flocking problem the external shape could also be controlled but it is not often done. In some applications when fixed positions are necessary, formations can be an advantage compared to flocking, [9] [10].

Formation control is presented in most of swarm robot applications because generally it requires a coordination control to obtain a strategic displacement or posture of the robots within the workspace to achieve a common work [11]. Recently, formation control problems of swarm robots have attracted many attentions, and several formation control schemes were proposed based on various strategies such as the behavior-based approach [12][13], leader– follower approach [14][15], virtual structure strategy [16][17], artificial potential based method [18][19] and graph theoretic method [20].

There are many issues need to be considered when build a formation control for swarm robot, such as the stability of the formation, controllability of different formation patterns, safety and uncertainties in formation [21][11].

Many researchers have made new formation control algorithm for finding new problem solving methods. Their novel algorithms, based on the swarm intelligence, have obtained good results. Among of the most popular and promising approaches is to estimate the uncertainty effects such as neural networks, fuzzy systems [22][23] and Particle Swarm Optimization (PSO) [24]. Fuzzy Logic technique is used for navigating swarm robots in unknown environment while Particle Swarm Optimization (PSO) is used for searching and finding the best position of target [25]. However, only few of existing results have been presented to solve the problem in the stability of the formation.

In this paper, it will discuss the main issues stability in formation with three classifications formation control approaches and its application in a dynamic environment and unknown.

II. CLASSIFICATIONS FORMATION CONTROL APPROACHES

Most studies on robot swarm cooperation have focused on formation control, which refers to the task of controlling a group of mobile robots to avoid collisions while maintaining the desired formation pattern and its application in a dynamic environment and unknown. Basically, methods that have been proposed for formation control, can be ategorized into three basic approaches : behavior based leader-follower and virtual structure.

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A. Behavior Based Approach

The behavior-based approach comes from the study of animal behaviors. In paper Balch and Arkin, 1998 presented a standard behavior-based technique, which consists of several behaviors including maintain-formation, avoid-static-obstacle, avoid-robot, and move-to-goal [12].

In behavior based, the behavior of each robot is generated as a time series of asymptotically stable states, which then contributes to the asymptotic stability of the overall formation control system. For this approach, its main advantage is that the collision avoidance problem can be easily dealt with due to the existing reactions between robot. However, the whole system is more complex and difficult to be analyzed mathematically [12]. It is also not possible to show that the system converges to a desired formation [26].

The approach that concerns with classification-based searching method for generating large-scale robot formation in paper [27] is presented to reduce the computational complexity and speed up the initial formation process for any desired formation. The behavior-based method is applied for the formation control of swarm robotic systems while navigating in an unknown environment with obstacles. Several groups of experimental results demonstrated the success of the proposed approach. These methods have potential applications for various swarm robotic systems in both the simulation and the practical environments. However, there is no clear definition to group behaviors for swarm robots, and it is difficult to guarantee the stability of a desired formation when the environment is complex [27].

Behavior-based approach is decentralized and may be implemented with less communication. As a decentralized implementation, behavioral approach enables agents derive controls for multiple competing objectives simultaneously. In addition, there is explicit feedback to the formation. The primary shortage is that group behavior cannot be explicitly defined [28].

TABLE I
RECENT RESEARCH IN BEHAVIOR BASED APPROACH

Year	Author	Application	Performance
1987	Reynolds [50]	cohesion, separation, alignment	simplistic, low complexity
1998	Balch and Arkin [12]	maintain-formation, avoid-static-obstacle, avoid-robot, and move-to-goal.	flexibility, robustness, stability
2003	Lawton et al [13]	maneuvers between formation patterns	effectiveness
2005	Soysal, O., Sahin, E [51]	approaching, repelling,and waiting together with obstacle avoidance	
2005	Bahceci, E., Sahin, E [52]	avoiding wall, formation keeping	performance and scalability
2009	Antonelly et al [53]	the reactivity to unknown or dynamical changing conditions	Flexibility, effectivenes
2011	Nasseri and Asadpour [54]	flocking target	simple, reach target is very short time
2014	Dali Sun et al [55]	to keep cooperating with others and to resolve path collisions	Scalability
2015	Dongdong Xu [27]	navigating in an unknown environment with obstacles	efficient, robust

B. Leader-Follower Approach

In the leader-follower approach, the leader robot maintains the given trajectory while the followers track a fixed relative distance from the designated neighboring robot. Approaches [13][15][29][30][31], the ability of a robot depends on its job. In the swarm, one or a few robots act as leaders which move along predetermined trajectories and other robots in the group follow while maintaining the desired relative position with respect to the leader. In most cases, leader- follower based robotic systems are implemented as centralized systems. However, most leader-follower algorithm approaches are still not complete. This is caused that the safe path, which gives a robot sufficient distance from obstacles and other robots, is difficult to derive [32].

The paper [31] established nonlinear gain estimates between the errors of the formation leaders and the interconnection errors observed inside the formation. In this way, it can characterize how leader inputs and disturbances affect the stability of the group. There is also a chance to assess the stability of particular subgroups inside the formation and thus it guides analysis.

A new leader-following control method for swarm formation. This paper described the formation task control and organizing the group robots to accomplish the formation task, and collision avoidance. Simulations have been presented show that the stability of the control algorithm can be achieved by tuning the parameters properly [33]. The algorithm can work well in any scales of formation. However, the environment is assumed to be obstacle free.

The leader-follower control strategy approach is more suitable for the situation where robots are initially localized near the formation pattern, in order to avoid collisions [28]. This paper investigat the decentralized formation control in case of parameter uncertainties, bounded disturbances, and variant interactions among robots.

TABLE II
RECENT RESEARCH IN LEADER-FOLLOWER APPROACH

Year	Author	Application	Performance
2004	Tanner et al [31]	maintaining the shape of a straight line	stability, performance and robustness
2005	Shao [15]	maintaining, obstacle-avoidance	simple, effective
2008	Xin Chen and Yangmin Li [56]	formation pattern	stability
2007	Mariottini et al.	maintain the formation.	Stability
2011	Viet-Hong Tran and Suk-Gyu Lee [33]	the formation task, or collision avoidance	stability
2013	Zhiyun Lin et al	the shape of a planar formation	asymptotically stabilize
2015	Kamel and Zhang	static and moving obstacles	convergen stability

C. Virtual Structure Approach

The concept of a virtual structure was first introduced in [14]. The proposed algorithm iteratively fits the virtual structure to the robots positions, displaces the virtual structure in some desired directions and updates the robots positions. In other literatures, this approach was used in the formation control of spacecraft [34] and marine vehicles.

In the virtual structure approaches the entire formation is regarded as a single structure where each robot is given a set of control to follow the desired trajectory of formation as a rigid body [34][35][17].

The main advantages of virtual physics-based design methods are: i) a single mathematical rule smoothly translates the entire sensory inputs space into the actuators output space without the need for multiple rules or behaviors; ii) the obtained behaviors can be combined using vectorial operations; iii) some properties (such as robustness, stability, etc.) can be proved using theoretical tools from physics, control theory or graph theory [23]. The virtual physics-based method is often used to design collective behaviors that require a robot formation.

D. Other Formation Control Approach

TABLE III
RECENT RESEARCH IN VIRTUAL STRUCTURE APPROACH

Year	Author	Application	Performance
1997	Tan and Lewis [14]	maintained	flexible, effective
2001	M. Egerstedt, X. Hu, and A. Stotsky	moving on the path	stability
2004	Ren and Beard [34]	maneuvers	effectiveness
2006	Lalish et al [17]	formation tracking	stability,
2011	Sadowska et al [57]	mutual coupling	robustness, stability
2013	Kahn et al [58]	guide a fleet of vehicles towards a target while avoiding obstacles	flexible, effective
2014	Benzerrouk et al	to attain the virtual targets	stable to attain the generated set-points

Other formation control approaches that are presented in this paper are potential fields and hybrid systems. Potential fields approach was introduced Schneider, F. E. & Wildermuth, D. In this method, different virtual forces belonging to robots, obstacles and the desired shape of formation are combined and used to move each robot to its desired position inside the formation. Similar to behavioral approach, the control derived based on several forces enables agents form a formation, while avoiding collision with obstacles or others. However the formation pattern (shape) needs to be disseminated in all members. Hence comparing with behavioral method, it needs more communication cost. One of the main drawbacks in using potential fields is the fact that delays in the communication channels may drive the system to instability [36].

Other examples of potential field approaches can be found in [37][38]., The paper in [39] presented a navigation function with a Lyapunov stable function. Lyapunov functions are used to prove closed-loop stability and to solve the local minima problem of potential fields.

Research in hybrid systems in [40] presented a formation control architecture that subsumes the leader-follower and the behavior-based approach. It specifically used a leader-follower strategy to build the formations, with the configuration geometry being accomplished by the chain of leaders and followers. The motor control of each robot relies on an attractor dynamics approach to behavior-based robot system, where formation behaviors for each leader-follower desired geometry and obstacle avoidance. The environment does not need to be known and may change over time. Implicitly, in the control architecture there are some important features such as establishing and moving the formation, spliting and joining of formations (when necessary to avoid obstacles). Robustness toward environmental perturbations is intrinsically achieved because the behaviour of each robot is generated as a time series of asymptotically stable states, which contribute to the asymptotic stability of the overall control system.

III. STABILITY CONTROL OF FORMATION CONTROL

The problem of formation stability has mainly been investigated by the Lyapunov stability theory and Graph theory.

A. Lyapunov Methods

Formation control and interconnected systems stability have been analyzed recently from many different perspectives. In behavior-based approaches [12] the group behavior emerges as a combination of group member behaviors, that is selected among a set of primitive actions. Lyapunov based techniques have been used extensively to establish asymptotic stability in formations.

Important work on swarm stability was given by Jin et al, 1994 and Beni et al, 1996. In Jin et al, 1994 they consider a synchronous distributed control method for discrete one and two dimensional swarm structures and proved stability in the presence of disturbances using Lyapunov methods. On the other hand, Beni et al, 1996, to best of author's knowledge, was the first recesrcher in the stability in asynchronous methods (with no time delays). In that paper, they consider a linear swarm model and provide sufficient conditions for the asynchronous convergence of the swarm to a synchronously achievable configuration.

The concept of control Lyapunov functions together with formation constraints in [16][4] is used to develop a formation control strategy and prove stability of the formation (i.e., formation maintenance).

On the other hand, the concept in [41] is based on using virtual leaders and artificial potentials for robot interactions in a group of agents for maintenance of the group geometry. By using the system kinetic energy and the artificial potential energy a Lyapunov function closed loop stability is proved. Moreover, a dissipative term is employed in order to achieve asymptotic stability of the formation.

A formation Lyapunov stability function in [16] is defined as a weighted sum of the control Lyapunov function for each vehicle to support the formation stability analysis.

In paper Liu and Passino (2004) and Gazi and Passino (2004b) used Lyapunov stability theory to prove that the behavior studied was able to let a swarm achieve coherent social foraging in presence of noise. Similarly, Gazi and Passino (2003, 2004a) proved that, in specific conditions, a swarm of agents aggregates in one point of the environment.

Moreover, paper (Hong et al, 2007) proposed a Lyapunov-based approach to give a sufficient condition to make all the agents converge to a common value, and a common Lyapunov function was explicitly constructed in the case of switching jointly connected topologies.

B. Graph Theory

The application of graph theory was discussed in [42]. A directed graph was used to represent the communication network and to relate its topology with formation stability. In another literature, Desai et al. 2001 presented a framework for describing the behaviors of robots in a formation, representing possible control graphs and the coordination of transitions with formation changes from one geometry to another.

The paper in [43] used a new approach based on edge-weighted graphs in order to define a new behavioral control strategy for a group of mobile robots moving in unknown environments. The formation shape and the avoidance of collisions between robots are obtained by exploiting the properties of weighted graphs. Since mobile robots are supposed to move in unknown environments, the presented approach to multi-robot coordination has been extended in order to include obstacle avoidance. The effectiveness of the proposed control strategy has been demonstrated by means of analytical proofs.

IV. FUTURE RESEARCH DIRECTIONS

Most studied on robot swarm cooperation have focused on formation control which refers to the task of controlling a group of mobile robots to follow predefined trajectory while maintaining the desired formation pattern [32]. Up to now, various control methods have been proposed and applied to the coordination design of robotic networks, such as behavior-based approach, virtual structure approach, the leader-follower approach and potential field approach.

Comparing with virtual structure approach, leader-follower paradigm can realize time-varying formation pattern. Even under complex conditions, such as uncertain parameters and unknown disturbances, individual control in leader-follower paradigm can guarantee formation stability. Hence, it is more easily realized in practical applications than generalized coordinates. As issue in the previous sections, there is an abundance of research work on many different aspects of formation control on swarm robotics systems. Stability analysis of formation implementations have been proposed using a variety of design methods [28]. However, one obvious problem is that the failure of one robot (i.e. leader) leads to the failures of the entire system [26].

Generally leader-follower based robot systems are implemented as centralized systems. Although centralized control has been used successfully [7], by relying only on one computing and command center, centralized control is prone to failure especially in dynamic and uncertain environments.

There still exists a number of open problems related to formation control on swarm robot, includes the formation stability analysis [44] and the application in a dynamic environment and unknown.

The key point is that swarm behavior can be triggered automatically by relatively simple rules followed by individuals. Although lots of applications have been developed for robotics system, it is still undiscovered in achieving completeness for a dynamic environment and unknown. Combining with traditional behavior-based control and swarm intelligence, our approach focuses on how to solve the problem stability on formation in a dynamic environment and unknown.

Formation control in unknown environment needs an approach that can deal with uncertain situation, where robustness properties must be intended in the control procedure. The control strategy in swarm robots formation must be simple algorithm with less computational ability, due to its onboard sensing and processing. Thus, simple control strategy with limited processing speed and memory space is desirable [45].

The main contribution presented in this paper is an approach based on swarm intelligence. It is introduced in order to define a new behavioral control strategy for swarm robots moving in unknown environments.

Among the most popular and promising approaches are based on swarm intelligence, such as to estimate and the uncertainty effects such as neural networks, fuzzy systems [23][46] and Particle Swarm Optimization (PSO) [47][48]. Fuzzy Logic technique is used for navigating swarm robots in unknown environment and Particle Swarm Optimization (PSO) is used for searching and finding the best position of target [25]. In order to obtain a safe path for all robots in unknown environment, IT2FLC algorithm is developed to maintain the swarm formation and avoid collision in complex environment [49]. Recent progress in technologies such as low computation, optimization still need to be analyzed.

Another important issue, that is being disregard in the systems and control literature, is the implementation and testing. In most case, the theoretical findings are being verified through computer simulations. However, for practical applications this may not be sufficient. Hence, there is a need for extensive experimental studies in the fields as well.

V. CONCLUSION

This paper presented a survey of formation control for swarm robotic system, a number of past studies where formation control of swarm robotic problems are analyzed and resolved with a swarm intelligence and optimization. By categorizing the existing results into the stability of formation with three classification formation control approaches and its applications a dynamic environment and unknown.

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