Academic Journal of Science and Technology
ISSN: 2771-3032 | Vol. 4, No. 2, 2022

Survey of Robot Formation Control Methods

Tao Xing[1], Yongchun Liu[1, 2], Lang Chen[1]

[1] College of Automation & Information Engineering, Sichuan University of Science & Engineering, Yibin Sichuan 643002, China
[2] Artificial Intelligence Key Laboratory of Sichuan Province, Yibin Sichuan 643002, China

Abstract: Robot formation control technology has a certain practical significance and application value. efficient and stable formation control is the theoretical basis and technical key to perform complex tasks. Firstly, the basic idea of formation control is introduced, and then several formation control methods such as following the leader method, behavior based method, virtual structure method and artificial potential field method are introduced; This paper summarizes the research achievements of robot formation control in recent 20 years at home and abroad. Finally, the future research direction of formation control is pointed out.

Keywords: Robot, Formation control, Multi agent technology, Cooperative control.

1. Introduction

The emergence of robots frees humans from dangerous, complex or completely unknown working environments [1-4]. The robot system can perceive various external environments in real time. It is a control management system with multiple functions such as visual recognition, task management, execution and allocation, and behavior decision-making. It can easily adapt to various harsh environments [5]. When some of the world's top professional chess players are defeated by the alpha dog with the powerful deep learning function of artificial intelligence, it represents the rapid improvement of robot intelligence. However, when a single robot performs complex work or is in a complex task environment, it simply cannot directly meet the needs of complex task processing through its own behavior. Therefore, people get inspiration from the movement of birds and ants flying in the nature, and use this kind of biological cluster formation cooperation to integrate it into the multi-body robot system, thus completing complex tasks that are difficult for a single robot to perform independently [6].

At present, the formation cooperative movement technology has been applied in many fields. In industry, by controlling multiple robots, various goods can be transported automatically in a specific way; In the military field, multiple autonomous mobile vehicles are widely used in military border patrol, resource geographical survey, reconnaissance and rescue, mine clearance or satellite attitude and motion coordination and space exploration; In the field of police affairs, multiple mobile robots are formed into an arc encirclement net to catch intruders, etc. [6]. Because the control system of multi-agent robot is widely used in many fields, the problem of multi-agent cooperative control has been paid more and more attention by researchers and engineers. In recent years, a large number of scientific research achievements have been made in the cooperative control of robot formation, and a variety of formation control methods, mainly represented by artificial potential field method, virtual structure method, behavior based control method, and following navigator method, have been gradually formed.

2. Problem Description

Formation control is mainly to study the control technology of robot system in the process of moving, which should not only follow certain formation constraints, but also adapt to the constraints of the current working environment. Its research contents can be divided into the following three aspects. (1) The fixed formation is completely suitable for tasks that have very strict requirements on the positions between robots. At this time, the relative position relationship between robots should be absolutely unchanged. (2) The task of incomplete maintenance of fixed formation allows the robot to deviate from its ideal formation position due to environmental factors during movement, and the robot system will try to recover the original formation as soon as possible after the deviation. (3) Switch in variable team formation, for example, the formation can be translated, rotated, expanded and contracted.

When designing a multi robot formation system, the following issues need to be considered: ① the ability of robots to avoid obstacles and prevent collisions; ② Accuracy of target or track tracking; ③ Effectiveness of mutual communication; ④ Stability of formation maintenance; ⑤ The controllability of different formation transformation.

For formation control, it is generally divided into two steps:

Step 1 Determine the target position of each robot according to the current environment, and its core is to select a reasonable corresponding target point for each robot. The actual robot cannot be regarded as a particle moving in any direction. If it detours in the target area or temporarily adjusts the position of the robot, it is easy to block. Therefore, the corresponding target points of each robot should be selected reasonably in advance, which can not only avoid the robot detouring in the target area, but also form a target formation as soon as possible.

Step2 Generates control commands according to certain control strategies to drive the robot to the target position in a certain formation. This step is the main body of the team task. In order to further meet the requirements of rapidity, each robot moves along the shortest path (ideal path) as far as possible, while avoiding obstacles in the process of movement.

In a word, multi robot formation control technology takes the queue composed of multiple robots as the research object, and its essence is the research of multi robot system. The purpose of the research is to find an effective method to analyze, design and control the multi robot system, so that it can complete the task effectively and with high quality.

3. Research Methods

There are many problems to be considered when studying the formation control of distributed multi robot systems, such as the stability of formation, the controllability of different formation modes, and the uncertainty of formation. Many methods have been proposed at home and abroad to solve these problems in formation control [7,8], including leader follower method, behavior based method, virtual structure method, artificial potential field method, etc.

3.1. Formation Control Method Based on Leader follower

The basic idea of the formation control method based on the Lead follower is that in a group composed of multiple robots, one robot is designated as the leader, and the rest is its follower, and the follower tracks the position and direction of the pilot robot at a certain distance interval. This method is extended to specify not only one leader, but also several to form a tracking chain, but only one leader in a group formation. According to the relative position relationship between the navigator and the following robot, different formations can be formed. Reference [9] proposed two feedback control methods to maintain formation, namely $l-\phi$ method. $l-\phi$ method is to keep the expected distance and relative angle between the leader and the follower; $l-\phi$ method is to keep the expected distance between the follower and the two pilots. At the same time, a controller design method based on input-output feedback linearization is proposed. Literature [10] used new $l-\phi$ and $l-l$ methods and added virtual repulsive force to prevent collisions between machines. Reference [11] designed the controller by introducing h reference point (virtual robot) and combining $l-\phi$ method. The advantage of this method is that the behavior of the entire robot formation can be controlled only by giving the behavior and trajectory of the leader, and the control is simple. The disadvantage is that it is not easy for the leader to get the tracking error feedback from the follower. If the leader moves too fast or the follower is blocked by obstacles, the formation may be damaged, which will affect the quality of task completion in serious cases. In the case of leader failure, if the design is not comprehensive and only relies on it, the consequences will be very serious. In general, it is necessary to adopt strategies such as specifying alternate leaders and changing leaders according to the situation in the design process to improve the system energy.

3.2. Formation control method based on virtual structure

The basic idea of formation control method based on virtual structure is to regard the whole robot formation as a rigid virtual structure. When the robot moves, it tracks a point on the virtual structure with a fixed relative position. The virtual structure method is often applied to the formation flight control of spacecraft and satellites [12]. This method can make a group of robots achieve rigid formation. The controller design of this method consists of three steps: first, define the desired dynamic model of the virtual structure; Secondly, the expected movement of the virtual structure is transformed into the movement of each individual robot; Finally, the tracking controller of each robot individual makes each robot track the corresponding points on the virtual structure. The virtual structure method, leader follower method and behavior based method are combined to apply to the formation control of multiple spacecraft. The formation control method based on virtual structure is a method of forming rigid formation, and formation feedback can be formed. The advantage of this method is that it is easy to specify the behavior of the robot group (virtual structure behavior), and can conduct formation feedback; The disadvantage is that it requires the formation to be a virtual structure, with a fixed relative position, rigid, and unable to consider the overall obstacle avoidance problem, so it is generally used in barrier free environments.

3.3. Behavior based formation control method

In the behavior based coordinated control method [13,14], each robot has some expected basic behaviors, including collision avoidance, obstacle avoidance, driving to the target, formation maintenance, etc. When the robot sensor is stimulated by external input, it reacts according to the input information of the sensor, and outputs a vector to represent the desired behavior of the robot. The control action of each robot is the weighted average vector of the control action of each basic behavior. In order to maintain formation and avoid obstacles, genetic algorithm can be used to determine the weight of control and select appropriate behavior [15]. In [16], the behavior of robot is based on an inclusive structure. Behavior based formation control can also be modeled with nonlinear dynamics system, and applied to trajectory generation and obstacle avoidance [17]. The disadvantage of this method is that the group behavior is not clearly defined, and it is difficult to conduct mathematical analysis and ensure the stability of the formation.

3.4. Formation control method based on artificial potential field

The early research on artificial potential field is mainly used to solve the robot path planning problem in static environment. However, the traditional artificial potential field is difficult for motion planning in dynamic environment. From the perspective of control theory, traditional path planning using artificial potential field method only introduces relative position as the input of feedback control, ignoring many important factors in dynamic environment. Since then, many literatures have cited the concept of artificial potential field, and improved this method to adapt to the distributed formation control of multiple robots.

Reference [18] proposed a general potential function to generate an effective and unique potential function by conveniently selecting the values of two groups of parameters. The application of the general potential function of formation makes it easy to switch between different formations, so it is not necessary to design different potential functions for different formations. In addition, obstacle avoidance and target tracking can also be integrated. Literature [19] proposed a distributed cooperative control method for multiple robots using artificial potential field and virtual leaders. The role of virtual leaders is to control the geometric shape and motion direction of multiple robot formation. Through several examples, this paper introduces the aggregation and formation movement under the action of virtual leaders, and analyzes the stability. This method is also used in literature [20] to achieve formation control of multiple robots in an obstacle free environment. This feedback control method allows a single robot to cut off its communication with a neighboring robot under certain circumstances to avoid collisions between robots and reduce excitation signals. The concept that each robot enters the blind area in this paper is that the robot in the blind area cuts off the communication with the adjacent robots. The so-called blind area means that each robot in its own blind area is only affected by its own virtual leaders, just like the blind person who does not exist in other adjacent robots, it will not communicate with other robots, The adjacent robots that are not in their own blind area will communicate with the robots in the blind area to actively avoid collision. When all robots are in their own blind areas, there is no need to communicate, so as to reduce the traffic. In document [21], a distributed path generation method in battlefield is introduced. In this paper, the source of potential field is subdivided into the potential field generated by adjacent robots, the potential field generated by obstacles, the potential field generated by threats, and the potential field generated by targets. The total potential field is the sum of these potential fields multiplied by the gain factor. The simulation of multi robot avoiding obstacles and covering the target area is also carried out, and the influence of the change of gain factor on the results is given. In reference [22], a controller based on artificial potential field is used to make the robot reach the desired formation, but they will change their motion to meet certain constraints (such as the effective distance of communication or camera and other sensors), which will make the system more robust.

4. Future Research Direction

For the research on formation control and its application, although there have been many breakthroughs in research over the years, there are still many problems to be further studied, mainly in the following aspects:

(1) Most formation control methods rely on the design method of the model, but there must be more or less gap between the physical model of the robot itself and the model built by the researchers, which may lead to the failure of the control method. Although the robustness and good anti-interference ability of multi-agent technology allow some errors in the model, in-depth mathematical analysis and simulation verification are still needed. Whether a formation control method can be developed systematically and does not depend on an accurate model is still one of the problems to be solved.

(2) Multi-agent theory has been very mature, but most of them are based on linear models. Because robots are basically complex nonlinear systems, these research results based on linear models cannot be directly applied to robots. How to use existing research results to explore multi robot formation control is also facing severe challenges.

(3) As multi-agent technology is based on the interaction between individuals to achieve the evolution of formation, the development of communication technology is crucial. The communication mode, bandwidth, and communication radius may constrain the design of the control protocol, and even affect the effect of task completion. In particular, the underwater communication technology has not yet broken through, which seriously restricts the development and application of underwater 3D formation cooperative control technology. At present, visual information is one of the breakthrough points that scholars try to solve the bottleneck of communication technology, but it is still in the exploration stage.

(4) Even though they are all based on multi-agent technology, the current methods to solve the problem of multi-agent formation control are still diverse and have different concerns. The most important thing is that the final control effect still largely depends on the development of hardware technology. Although some scholars have tried to avoid the difference of control effect caused by imperfect hardware conditions by upgrading hardware technology and applying various intelligent control algorithms, there is still a long way to go.

(5) The pre formation control era is mainly for small-scale multi-agent systems. In the post formation control era, how to solve the formation control problem of large-scale systems becomes the first problem to be solved. Distributed control protocols are very conducive to the expansion of multi-agent systems, and are suitable for solving the coordination problem of large-scale systems. But there are still many difficulties. For example, the distributed control protocol is very effective for large-scale systems. For the formation control problem of small-scale systems, which is more effective, distributed protocol or centralized protocol? How to use radio frequency communication and visual communication more effectively? Most distributed protocols are based on the relative position, relative attitude and other information between agents. How to use limited hardware conditions to obtain the above information as accurately as possible? Etc.

5. Conclusion

In this paper, the research progress of multi-agent formation control and its derivatives at home and abroad in recent years is reviewed, and the possible development directions of some problems related to multi-agent formation control are listed. The research on problems related to multi-agent formation control involves a wide range of contents. It is believed that in the next decade, many problems related to formation control will be solved with the development of other related disciplines and technologies, and will also be applied in more fields.

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