A FRAMEWORK OF FORMATION CONTROL APPLYING TO MULTI-ROBOT SYSTEMS

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ABSTRACT

In recent decades, the deployment of multi-robot systems (MRS) has created enormous research interests such as control and communication, task allocation, cooperative coordination, etc. Among these areas, formation control for MRS becomes an active research topic and has received much attention from scientists due to its superior advantages compared with other conventional systems. In this paper, we review formation control strategies and propose a control protocol for the formation of MRS. The formation of MRS moves to the target point by following a leader. The formation shape can be reconfigured to avoid collisions with obstacles by utilizing an artificial potential field method. The simulation is provided to prove the effectiveness of the method.

Keyword *Multi-Robot System (MRS), Formation Control, Artificial Potential Field (APF)*

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1. INTRODUCTION

With the advanced development of the robotics field, multi-robot systems (MRS) are becoming an active research topic and applied in various fields, such as military surveillance and patrol [1–3], search and rescue operations [4–6], remote sensing operations [7–11], inspect buildings and infrastructure [12–15], manage and monitor crops in agriculture [8,16–18], transporting goods [19]. In practice, moving and working in formation has many advantages over a single robot, for example, MRS can increase the anti-interference performance and efficiency, improve the probability of success in search tasks, expand the region of surveillance and reduce the expense of military missions, increase the robustness and efficiency of the system while providing redundancy, reducing system costs, and completing complex tasks in a vast area.

While working in a group, each robot travels to different places and collaborates with its neighbors to complete a given task. MRS needs to avoid collisions from obstacles and also among the other partners. In some tasks, MRS may be required to autonomously operate in dangerous environments that easily cause failures of MRS and communication interruption. Recently, formation control problem is received great attention from many researchers to develop effective algorithms that hopefully overcome the challenges. Hence, formation control plays a crucial role in coordinated control for a group of mobile robots. This controlling problem required a group of autonomous vehicles to follow a predefined trajectory while maintaining a desired spatial pattern. In many application scenarios, a team of multi-robots needs to follow the preset trajectory while maintaining a specific geometric shape.

In formation control for MRS, various strategies have been proposed to solve the challenges including leader-follower, virtual structure, behavior-based, etc. As far as missions for MRS become more complicated with more strict conditions in terms of scalability, robustness, etc., it is necessary to have an overview of the control strategies with advantages and limitations.

In this work, the focus is a concise review of the existing research on the formation control strategies of MRS and then a control protocol for the formation of MRS is proposed. The review emphasizes specific manners on the advantages and limitations of each strategy are presented, which supports researchers in easily choosing suitable formation control design methods for their specific problems. The proposed method combines a leader-follower approach with an artificial potential field (APF), namely that the followers in formation are led by a leader and collision avoidance ability is ensured by the use of APF method. This control method has the advantages of both a leader-follower framework and an artificial potential field, which is effective, and easy to implement.

The rest of the paper is organized as follows: Section 2 provides formation control schemes and mechanisms, respectively that clarify research directions in the fields. The benefits and challenges of each method are also discussed in this section. The proposed method that combines a leader-follower framework with APF method is presented in section 3. Finally, the conclusions and future developments are provided in Section 4.

2. FORMATION CONTROL STRATEGIES

In general, there are three integral problems that need to be considered in the formation control. Firstly, the formation generation task drives the robots which are in random situations to form the desired formation topology. Secondly, the control strategies have to ensure that the desired shape of the formation must be retained while the team performs the operations. The last one is the formation reconfiguration. When working in different environments, the formation of MRS may be subjected to different types of faults such as loss of connections among the robots in the group, facing obstacles, etc. When MRS encounters these kinds of problems, the formation topology must be re-established to adapt to the new conditions. Various formation control strategies have been discussed in this section.

2.1 Leader-Follower Approach

The leader-follower scheme is the most common method in formation control due to its simple control structure and scalable ability [20]. In this approach, a member of the group is assigned as a leader, whereas the other members are considered followers. The leader has full access to the global information, and its trajectory is the reference for the rest of the followers. All the followers can sense the relative distances between them and the leader. The local control strategy of the followers is to maintain these relative distances while performing other tasks.

The leader-follower approach has the advantage of a simple formation control structure. A formation controller only requires the leader’s trajectory and the desired position relation between the leader and followers to compute control commands [21].

The limitation of the leader-follower mechanism is less robust. The trouble of the leader can cause the fall of the entire formation. To overcome this disadvantage, another approach in the leader-follower scheme is proposed as virtual leaders [22, 23]. Besides, the leader-follower scheme has another disadvantage in that the leader has no feedback from followers, which may cause collisions between robots. In addition, obstacle avoidance has not been considered in most of the research on this leader-follower protocol. When a formation of robots is operating in unknown environments, the ability to avoid obstacles of a robot is a critical matter.

2.2 Behavior-Based Approach

The concept of a behavior-based approach is firstly introduced in [24]. In this method, each individual robot in the group shows several behaviors based on sensory inputs such as goal-seeking, formation keeping, obstacle avoidance, etc., and then final control is derived from the evaluation of the relative importance of each behavior [25- 27]. This approach is a coordinated control structure that is based on the behavioral schema and various vector control functions, these vectors represent the response received from the sensors. The final action of each robot is a weighted average vector with a value depending on the priority of the behaviors. Therefore, the final control command for a robot is calculated by combining the product of the outputs of the behavior and its weight values.

Because it only uses local sensor information, this approach enhances the autonomy of MRS and works well in different environments. This strategy is also capable of dealing with the multiple-goal mission. However, the disadvantages of this method are difficult to model and have low stability. Besides, they have a large amount of computation and require highly technical tools in the selection of behavioral weight values

2.3 Virtual Structure Approach

The virtual structure approach is firstly introduced for controlling the formation of mobile robots [28]. The concept of this method is that the shape of the formation is treated as a rigid body, and then the desired formation is established by fitting the physical position of the formation to the position of the virtual body. In other words, a virtual rigid structure is derived that represents a form of robots. Then, the desired motion of the virtual rigid structure is given, and the robot motion is derived from the given rigid structure. Finally, to track the robots in the group, a tracking controller for each robot is designed in which the formation of MRS is maintained by minimizing the error between the virtual structure and the current robot position.

In terms of advantages, the desired trajectory is not assigned to the single robot but is shared by the whole team. Therefore, this approach is easy to prescribe coordinated behavior for the whole group. The limitation of this approach is centralized, this leads to a consequence that a small failure can also crash the entire system [29-31].

2.4 Artificial Potential Field

The main idea of Artificial Potential Field - APF is to create a virtual artificial potential field. In the potential field, each robot will be affected by the attractive or repulsive force from different objects. The force is represented by potential functions. The movement of the robot is eventually decided by the resultant of different abstract forces suffered by the robot. Repulsive forces are exploited to help robots efficiently avoid collision with external obstacles as well as other members. Based on the above mechanism, APF approach is commonly used in multi-robot collision avoidance. Therefore, it is can ensure safe operations for MRS. Furthermore, hybrid methods combining an APF approach with traditional strategies have also been carried out in recent related research [32-35].

The artificial potential field method is easy to understand and the associated control method is simple and does not require complex computations, it is likely to become a potential strategy for control of robots like UAVs which can normally carry limited hardware.

3. APF-BASED CONTROL PROTOCOL UNDER LEADER-FOLLOWER FRAMEWORK

As mentioned above, the leader-follower scheme has a disadvantage in that the leader has no feedback from followers, which may cause collisions between robots. In addition, obstacle avoidance has not been considered in leader-follower protocol. When a formation of MRS is operating in unknown environments, the ability to avoid obstacles of a robot is a critical issue. An efficient path planning method is APF, which is commonly used in multi-robot collision avoidance. In this section, the paper proposes a control scheme utilizing an APF-based control protocol under a leader-follower framework and the results will be proved by simulation.

3.1 Control Scheme

Considering n robots in two-dimensional space. Because the dynamics of formation control loops is slower than attitude control loops, the dynamics of a robot can be described by a second integrator model when analyzing formation control problems. The ith robot dynamics is given as:

$$\begin{cases} \dot{p}_i = v_i \\ \dot{v}_i = u_i \end{cases}, i \in \{1, 2, ..., n\} \tag{0.1}$$

where $p_i = (x_i, y_i)$ is the position of the robot i, v_i is velocity of robot, and u_i is control inputs.

The simple principle of APF is established by global calculation of obstacles in the system. With the known starting point, terminal point and obstacle location, an APF is constructed to imitate the existing potential energy mechanism in nature. The moving object in the environment is regarded as a particle in the APF, which moves in the APF established by the global calculation of obstacles. In this method, the virtual force field is obtained by negative gradient calculation. It is composed of 2 components: the attraction field towards the target point and the repulsion field far away from the obstacle.

The resultant potential field is calculated according to the following equations:

$$U(p) = U_{att}(p) + U_{rep}(p) \tag{0.2}$$

where $U_{att}(p)$ is the attrative field, $U_{rep}(p)$ is the repulsive field.

The attraction potential function is calculated as:

$$U_{att}(p) = \frac{1}{2}\alpha\rho^2(p, p_{goal}) \tag{0.3}$$

where α is a positive constant, $\rho(p, p_{goal})$ is the relative distance between a robot and a target. The corresponding attraction $F_{att}(p)$ is the negative gradient of the potential field function of the target, and the direction points to the point of the target. In the process of the robot flying to the target point, the attraction converges to zero linearly.

$$F_{att}(p) = -grad[U_{att}(p)] \tag{0.4}$$

The repulsive function is given as:

$$U_{rep}(p) = \begin{cases} \frac{1}{2}\beta\left[\frac{1}{\rho(p, p_{obs})} - \frac{1}{\rho_0}\right], \rho \le \rho_0 \\ 0, otherwise \end{cases} \tag{0.5}$$

where β is a positive constant, $\rho(p, p_{obs})$ is the relative distance between the particle and the obstacle, and ρ_0 is the radius of influence of the repulsive force of the obstacle. The corresponding repulsive force $F_{att}(p)$ is the negative gradient of the target potential field function.

$$F_{rep}(p) = -grad[U_{rep}(p)] \tag{0.6}$$

A formation of n robots, each robot is affected by the combination of the artificial forces namely attractive forces between robots, repulsive forces between robot, and repusive forces between robots and obstacles. The target attraction force only affects a leader robot.

The attractive force between robots is to ensure that a robot-formation is not separated. Considering the i^{th} ROBOT has a position $p_i(x_i,y_i)$, the j^{th} robot has a position $p_j(x_j,y_j)$. The relative distance between two robots is $\rho_{ij} = \rho(p_i, p_j)$, the magnitude of ρ_{ij} calculated by $|\rho_{ij}| = \sqrt{(x_i - x_j)^2 + (y_i - y_j)^2}$

The attractive potential field and attrative force of i^{th} robot created by j^{th} robot are given as

$$U_j^{att}(i) = \frac{1}{2}\alpha\rho_{ij}^2 \tag{0.7}$$

$$F_j^{att}(i) = -grad(U_j^{att}(i)) = \alpha.\rho_{ij} \tag{0.8}$$

In the formation, the i^{th} robot is driven by the combined attractive force of other robot members

$$F_{att}(p_i) = \sum_{j=1, j\ne i}^{N} F_j^{att}(p_i) \tag{0.9}$$

The repulsion force between robots is to guarantee a certain distance between robots, so collisions between robots can be avoided.

The relative distance between two robots is given by $|\rho_{ij}| = \sqrt{(x_i - x_j)^2 + (y_i - y_j)^2}$. The repulsive force is given by:

$$U_j^{rep}(p_i) = \begin{cases} \frac{1}{2}\beta\left[\frac{1}{|\rho|} - \frac{1}{\rho_0}\right]^2, \rho \le \rho_0 \\ 0, otherwise \end{cases} \tag{0.10}$$

where β is the constant gain of repulsion, ρ_0 is a constant indicating the influence region of repulsion force. The repulsion force is the negative gradient of the repulsion field, and the direction is far away from the robot as a dynamic obstacle. The repulsion force of the i^{th} robot caused by the j^{th} robot can be defined as:

$$F_j^{rep}(p_i) = \begin{cases} \beta\left[\frac{1}{|\rho_{ij}|} - \frac{1}{\rho_0}\right]\frac{1}{|\rho_{ij}|^2} \\ 0, otherwise \end{cases} \tag{0.11}$$

The total repulsive forces applied on the ith robot is given as:

$$F_{rep}(p_i) = \sum_{j=1, j\neq i}^{N} F_j^{rep}(p_i) \tag{0.12}$$

The obstacles avoidance ability of a robot is provided by introducing repulsion generated by obstacles. Assuming the ralative distance between a robot and an obstacle is expressed as $\rho_{io} = \rho(p_i, p_o)$ with p_i is the position of robot ith and p_o is the position of obstacle. Then, the repulsion field at position p_i created by an obstacle is calculated by:

$$U_{rep}(p_o) = \begin{cases} \frac{1}{2}\beta\left[\frac{1}{|\rho|} - \frac{1}{\rho_0}\right]^2 \rho^{\sigma}(p_i, p_{goal}), \rho \le \rho_0 \\ 0, otherwise \end{cases} \tag{0.13}$$

where β is the repulsion gain and ρ_0 is a constant representing the influence region. σ is a positive constant, which is used to ensure the global minimal of the total potential field only at the target place p_{goal}.

The repulsion force is calculated by taking negative gradient of the repulsion field. The direction of the repulsive force is away from the obstacles. We consider a set of M obstacles $v_M = (1, 2,...,M)$. As long as a robot has not reached the destination, the repulsive force acting on the ith robot caused by obstacles in the working environment is defined as:

$$F_{p_i}^{rep}(p_o) = \sum_{o=1}^{M}\beta\left[\frac{1}{|\rho_{io}|} - \frac{1}{\rho_0}\right]\frac{1}{|\rho_{io}|^2}\rho^{\sigma}(p_i, p_{goal}) \tag{0.14}$$

To lead a formation to the destination, a robot in group is chosen as a leader. The leader has the information of the target position. This information is utilized to compute attractive forces generated by the target acting on the leader.The relative distance between the leader and the target point $p_g(x_g, y_g)$ is given by $\rho_{goal} = \rho(p_i, p_g)$. Then, the attractive field and attractive force are calculated by:

$$U_{att}(p_i) = \frac{1}{2}\alpha(\rho(p_i))_g^2 \tag{0.15}$$

$$F_{att}(p_i) = \alpha.\rho_g(p_i) \tag{0.16}$$

The control protocol is updated in a distributed manner. Each robot obtains the relative position of ostacle and target through the sensing data. Then these data are converted into position information with respected to global coordinates. The APF controller utilizes these data to compute command signals.

3.2 Results

A simulation for a formation of four robots is given to validate the effectiveness of the proposed methods. Three followers track the leader's trajectory and keep a certain distance from the leader. The initial positions of four UAVs are respectively Leader *(25,25)*, Follower 1 *(25,10)*, Follower 2 *(25,30)*, Follower 3 *(10,25)* as in Figure 1. The destination positions has a position at *(70,25)*

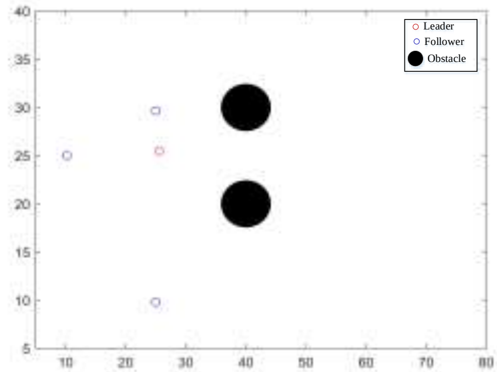

Fig -1: Initial potions of four robots

Figure 2 shows a situation in which the multiple robot system changes formation to avoid obstacles. After escaping the obstacles area, robots continue moving toward the destination correctly as shown in Figure 3.

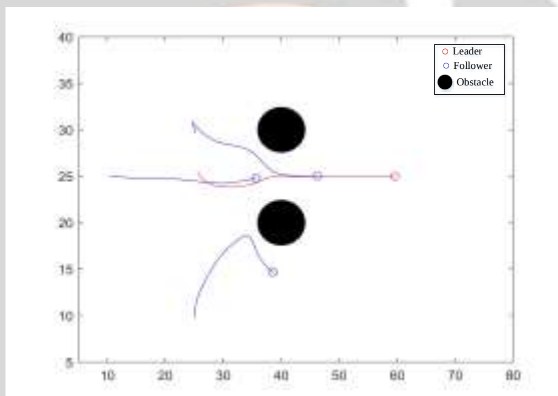

Fig -2: Robots maneuver to avoid obstacles

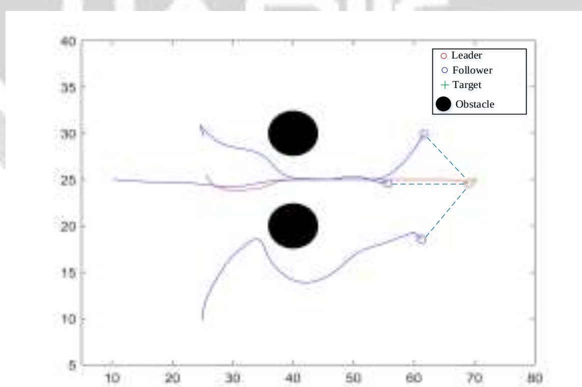

Fig -3: Robots formation reaches the target

4. CONCLUSIONS

In the paper, we discussed the main features of the formation control strategies in the existing research and presented a formation control protocol for MRS under the leader-follower strategy. Then artificial potential forces were designed for MRS which was adopted to avoid obstacles by formation reconfiguration. The proposed method utilizes the advantages of two control strategies, which are simple, effective, and easy to implement. The effectiveness of the proposed approach was demonstrated by simulation. In future works, the issues such as obstacle altitude, flight attitude, and practical experiments will be considered.

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