# Chapter 23
# Shape Control of Robot Swarms with Multilevel-Based Topology Design

**Xiao Yan**
*City University of Hong Kong, China*

**Dong Sun**
*City University of Hong Kong, China*

## ABSTRACT

*Significant attentions have been drawn to the cooperative control of robot swarms from researchers all over the world during the past decade. This chapter mainly focuses on the shape control problem of a group of homogeneous mobile robots moving into a desired region. A novel topology design of the robot group is proposed with a multilevel-based structure, which can be utilized to construct different shapes for the robot group within the desired region. A controller employing several potential forces is developed to control the robots in forming the desired formation shape while avoiding collisions during their movements. The local minima problem which may cause the robots stuck at undesired positions is further addressed with a novel shape regulation control force. The stability of the controlled system is analyzed using a Lyapunov approach. Simulations and experiments are demonstrated to show the effectiveness of the proposed approach.*

## INTRODUCTION

Swarming behavior can be observed in nature in many organisms ranging from simple bacteria to mammals. For example, individuals may respond directly to local physical cues such as concentration of nutrients or distribution of some chemicals, which may be laid by other individuals. This process is called chemotaxis, which is used by organisms such as bacteria or social insects (e.g., by ants in trail following or by honey bees in cluster formation). Swarming behavior is driven by various advantages of such collective and coordinated behavior for avoiding predators and increasing the probability of

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finding food. Inspired by this, a large number of robots are usually deployed for task accomplishment in the form of multirobot systems. Typical swarming behaviors of robots include but are not limited to aggregation, flocking, task allocation, and pattern formation. In addition, robots moving in specific geometrical formations are believed to be capable of reducing system costs and increasing system robustness and efficiency while providing redundancy, reconfiguration capability, and structural flexibility (Chen et al., 2005). In all these problems, the robots must be able to organize and generate complex shapes, often maintaining constraints with respect to neighbors for communication.

Extensive studies have been recently conducted for the shape control of multirobot systems, including leader-follower (Chen et al., 2010; Consolini et al., 2008; Das et al., 2002; Desai et al., 2001; Gu & Wang, 2009; Huang et al., 2006), behavior-based (Balch & Arkin, 1998; Marino et al., 2009), and virtual structure methods (Egerstedt & Hu, 2001; Ren & Beard, 2004), among others. In the leader-follower method, some robots are designated as leaders with predefined trajectories, and the followers generally need to maintain a desired distance and orientation with respect to their respective leaders. Though this method is easy to analyze, an obvious disadvantage is that the failure of the leader may lead to the failure of the whole system. For the behavior-based approach, a set of desired behaviors is employed onto individual robots. By defining various weightings on different behaviors, the overall performance of a system can be achieved by averaging the overall weightings. However, the overall system is difficult to be analyzed mathematically and it is also impossible to show the convergence to a desired shape/formation. In the virtual structure method, the entire formation is considered as a single entity and the desired motion for each robot is assigned according to the structure, which must be rigidly maintained during the movement. The drawbacks for the virtual structure method mainly lie in the difficulties of formation changing and obstacle avoidance. Other formation approaches have also been reported in the recent literature.

A synchronization approach was proposed to trajectory tracking of multiple mobile robots while maintaining time-varying formations (Sun et al., 2009). Each robot was controlled to track its desired trajectory while synchronizing its motion with other robots to keep relative kinematics relationships, which can converge both position and synchronization errors to zero asymptotically. A graph theory-based method was used to model the communication network and eigenvalues of the graph Laplacian matrix were employed to determine the effect of the communication topology on formation stability (Fax & Murray, 2004). Path planning problems were considered for multirobot formations to generate collision-free paths (Kloder & Hutchinson, 2006; Liu et al., 2011). However, most of these approaches were not specifically designed for shape control of large-scale robot groups.

The potential field-based approach has been considerably used for controlling a large group of robots because of its advantage in controlling the robot swarms such that individuals stay together as a whole without collision. Artificial potential functions and the sliding-mode control techniques were used for multiagent coordination and control (Gazi, 2005). A theoretical framework was presented for design and analysis of distributed flocking algorithms (Olfati-Saber, 2006), and the cases of free-flocking and flocking with obstacle avoidance were both addressed. However, the potential field-based method has difficulty in driving the robot swarms to form specific desired shapes, and selecting potentials to achieve global convergence is also difficult.

When handling a large number of robots, the idea of initially controlling robot swarms into a desired region and then forming the desired shapes subsequently can be feasibly realized. For example, implicit functions were used to generate specific curve and the robot swarms were controlled to spread along the desired curve (Chaimowicz et al., 2005). To have a high degree of control over the desired 2D curves, the