Chapter 5

COOPERATIVE CONTROL OF ROBOT FORMATIONS

Rafael Fierro, Peng Song, Aveek Das, and Vijay Kumar
GRASP Lab. University of Pennsylvania, Philadelphia PA, USA
rfierro, pengs, aveek, kumar@grasp.cis.upenn.edu

Abstract We describe a framework for controlling and coordinating a group of nonholonomic mobile robots equipped with range sensors, with applications ranging from scouting and reconnaissance, to search and rescue and manipulation tasks. We derive control algorithms that allow the robots to control their position and orientation with respect to neighboring robots or obstacles in the environment. We then outline a coordination protocol that automatically switches between the control laws to maintain a specified formation. Two simple trajectory generators are derived from potential field theory. The first allows each robot to plan its reference trajectory based on the information available to it. The second scheme requires sharing of information and enables a rigid group formation. Numerical simulations illustrate the application of these ideas and demonstrate the scalability of the proposed framework for a large group of robots.

Keywords: formation control, potential functions, nonholonomic mobile robots, switching control.

1. Introduction

It is well known that there are several tasks that can be performed more efficiently and robustly using multiple robots, see for example [19]. Multi-robot applications include cooperative manipulation, navigation and planning, collaborative mapping and exploration, and formation control. In fact, there is extensive literature on motion planning and control of mobile robots in structured environments. However, traditional control theory mostly enables the design of controllers in a single mode of operation, in which the task and the model of the system are fixed. While
control and estimation theory allows us to model each behavior as a dynamical system, it does not give us the tools to compose behaviors or the hierarchy that might be inherent in the switching behavior, or to predict the global performance of a highly complex multi-robotic system.

The key contributions of this paper are (1) a set of control algorithms and a coordination strategy that allow the robots to maintain a prescribed formation, and (2) a newly developed trajectory generator that combines potential functions and the dynamics of visco-elastic contacts. By combining control, coordination, and trajectory generation we are able to compose single control modes or behaviors and build formations in a modular fashion. Moreover, we can guarantee that under reasonable assumptions the basic formation is stable. Thus, the group can maintain a desired formation and flow towards its goal configuration. The ability to maintain a prescribed formation allows the robots to perform a variety of tasks such as collaborative mapping and exploration, and cooperative manipulation [22].

We divide the multi-robot cooperative control problem into two areas: (a) formation control and (b) trajectory generation. Formation control approaches can be classified into three main categories as in [4]: leader-following, behavioral and virtual structures. In the leader-following one robot acts as a leader and generates the reference trajectory for the team of robots. Thus, the behavior of the group is defined by the behavior of the leader. In the behavioral approach, a number of basic behaviors is prescribed, e.g., obstacle avoidance, formation keeping, and goal seeking. The overall control action (emergent behavior) is a weighted average of the control actions for each basic behavior. In this case, composing control strategies for competing behaviors and implementing them can be straightforward. However, formal stability analysis of the emergent group behavior may be difficult. Finally, virtual structures consider the entire formation as a rigid body. Once the desired dynamics of the virtual structure are defined, then the desired motion for each agent is derived. The framework proposed in this work is flexible enough to accommodate any of these formation control approaches. It is the designer’s decision to use decentralized reactive behaviors with no leader involved, leader-following, or rigid body motion to perform a given task. We will demonstrate this through numerical simulation experiments.

The problem of multi-robot trajectory generation is to generate collision free trajectories for mobile robots to reach their desired destinations. Previous approaches in this area can be broadly divided into two classes including graph based planners [3], and potential field methods [14, 15]. In this work we consider the latter. Artificial potential field approaches are based on constructing repulsive potential functions around obstacles