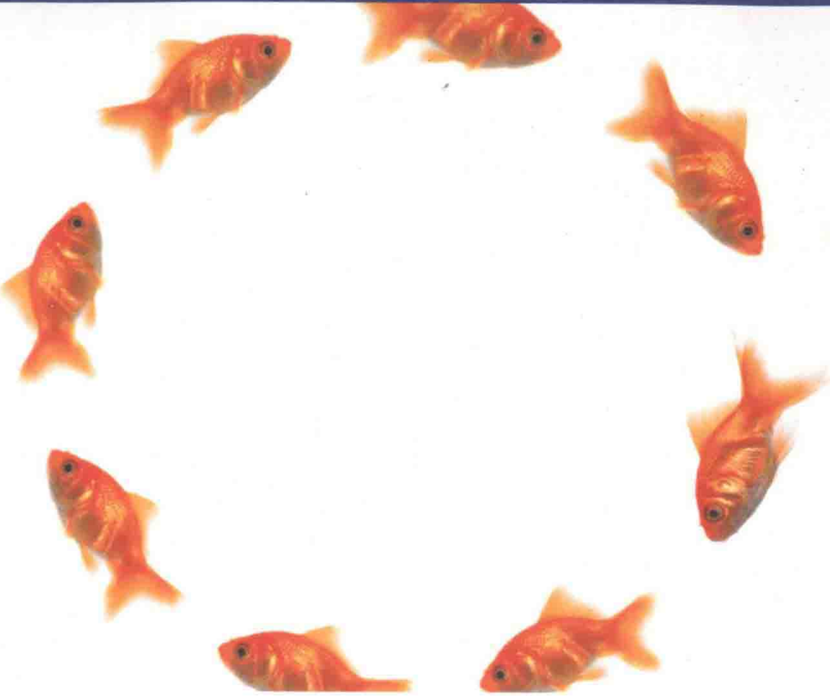

Nusrettin Güleç

COORDINATED MOTION

MODELING AND CONTROL FOR MOBILE ROBOT GROUPS

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to my beloved sister

&

my father

&

my mother

Biricik Ablama

&

Babama

&

Anneme

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Chapter 1

Introduction

Science today is essentially about establishing models that mimic the behavior of real-life systems to be able to predict the outcome of certain events encountered in nature. Models for technical issues like electrical, mechanic, pneumatic and hydraulic systems as well as social issues like economic growth of countries and population growth of communities have been well-established and developed. However, subjects related to intelligent behavior observed in nature such as coordinated motion and coordinated task handling of social groupings along with the autonomous behavior of individual agents in those groups are still in the phase of research. Many studies have been directed towards understanding and modeling the way of biological systems, particularly humans and animals performing certain tasks together. A variety of scientific disciplines - such as artificial intelligence, mechatronics, robotics, computer science and telecommunications - deal with these problems from different aspects. For example, artificial intelligence researchers work on establishing a framework for the algorithms to be followed by each autonomous individual in the group to achieve coordinated motion of the entire group, while researchers in the area of telecommunications are interested in developing methods for efficient transfer of necessary data between the autonomous elements of the group.

The research effort towards modeling the coordinated behavior of natural groupings has triggered the studies on several other areas such as decentralized systems, distributed sensing, data fusion and mobile robot vision.

The following sections outline the basic concepts regarding the coordinated motion of a group of autonomous mobile robots. The last section of the chapter is devoted to the formulation of the problem that will be attacked in this book.

1.1 Coordinated Motion and Coordinated Task Manipulation

Modeling groups of autonomous mobile robots engaged in coordinated behavior has been of increasing interest in the last years [1] - [19], [23] - [27], [49]. The applications of such a research field include tasks such as exploration, surveillance, search and rescue, mapping of unknown or partially known environments, distributed manipulation and transportation of large objects, reconnaissance, remote sensing, hazard identification and hazard removal [2], [6]. In particular, robotic soccer has been an important application area and eventually became a diverse and specific problem towards which many studies have been carried out [20] - [22].

The term *coordinated motion* generally denotes the motion of systems, which consist of more than one robot where the motion of each is dependent on the motion of the others in the group, mostly to accomplish a coordinated task. *Coordinated task manipulation* by a group of mobile robots, on the other hand, is defined as the accomplishment of a specified task together in certain formations. The necessary formation may vary based on the specifications of the coordinated task [10]. A rectangular formation could be better to carry a heavy rectangular object whereas circular formations might be better for capturing and enclosing the invader to provide security in surveillance areas [12], [13].

Robotics has made great steps forward, triggering the development of individual autonomous mobile robots, while multi-robot systems research lags behind. The reason for this lagging lies in the fact that coordinated motion of a group of autonomous mobile robots is a very complicated problem. At the highest level, the overall group motion might be dealt with by viewing such a collection as an ensemble. On the other hand, at the lowest level distributed controls must be implemented which ensure that the robots maintain safe spacings and do not collide. The following problems are fundamental to multi-robot researchers [15]:

- Multi-robot system design is inherently harder than design of single robots.
- Multiple robots may distract activities of each other, in the extreme precluding the team from achieving the goal of the mission.
- A team may have problems with recognizing the case when one or more team members, or the team as a whole, becomes unproductive.
- The communication among the robots is a nontrivial issue.
- The "appropriate" level of individualism and cooperation within a team is problem-dependent.

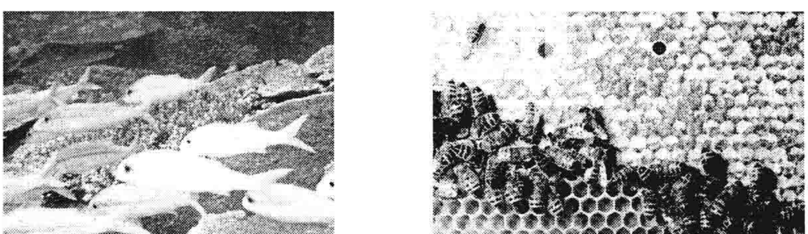
The autonomous robots forming the group must avoid collisions with other members of the group and any other static or dynamic obstacles. Collision turns out to be one of the most essential problems in the context of coordinated motion [19]. Moreover, collision avoidance is the premier factor in generation of the reference trajectories to yield coordinated motion; i.e. the robots should change their path to avoid collisions even if this will introduce some delay for the achievement of the specified coordinated task.

1.2 Decentralized Systems

Computer science encountered a serious bottleneck with the increasing computational demand of applications such as databases and networks due to limited computational power. The idea of *decentralized systems* emerged in computer science society to fulfill such demands [23].

Flocking birds, schooling fish (see Fig. 1.1(a)) and bees building a honeycomb in the beehive (see Fig. 1.1(b)) are examples of decentralized groupings in nature, where each member works in coordination with the others [3]. In effect, coordinated motion of multiple autonomous mobile robots is an important application area for decentralized systems. In particular, multi-robot systems are different from other decentralized systems because of their implicit "real world" environment, which is presumably more difficult to model compared to traditional components of decentralized system environments like computers, databases and networks. As a result of the wide application areas, the research efforts towards developing such systems has been monotonically increasing in the last decade [24] - [30].

The research efforts towards the development of decentralized robotic systems revealed the fact that, there are several tasks that can be performed more efficiently and robustly using distributed multiple robots [10]. The classical example of decentralized robotic systems is



(a) (b)

Figure 1.1: Decentralized natural groupings: (a)Schooling fish (b)Honey bees

space exploration [15]. Another example is the exploration and preservation of the oceanic environments, the interest in which has gained momentum in recent years [25]. Following are the most appealing advantages of decentralized systems over centralized systems for robotics applications:

- Failure of a single robot in centralized systems results in system failure, whereas this will not necessarily jeopardize the whole mission assigned to a team in decentralized systems.
- Economic cost of a decentralized robotic system is usually lower than that of a centralized system that could carry out the same task, especially in the case when component failure is encountered [27].
- A huge single robot, no matter how powerful it is, will be spatially limited while smaller robots could achieve the same goal more efficiently.
- Decentralized systems outclass centralized systems in tasks such as exploration of an area for search and rescue activities [23].

1.3 Computer Vision for Mobile Robots

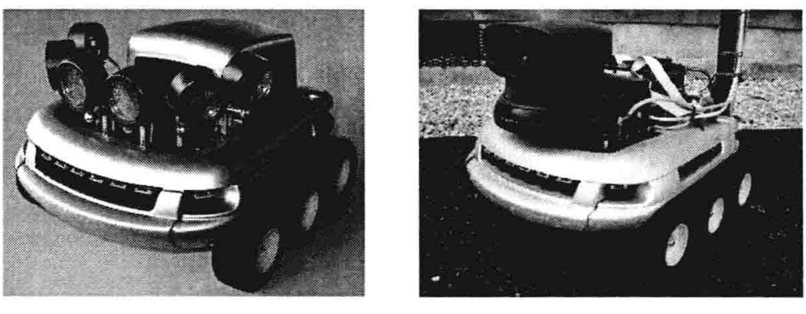
Sensing of the environment and subsequent control are important features of the navigation of an autonomous mobile robot. Hence, each member in a decentralized robotic system should gather information about its environment via some sensor during the manipulation of a specified coordinated task. This is crucial for a variety of tasks during navigation such as target detection and collision avoidance, which are common in most coordination scenarios. Although numerous types of sensors exist in the market, two main types have been widely used in the context of coordinated motion. Ultrasonic range sensors mounted around the mobile robot as seen in Fig. 1.2(a) have been used to obtain distance information between the robot and any physical existence in its environment. Onboard camera(s) mounted on the mobile robot as depicted in Fig. 1.2(b) have been applied together with techniques from computer vision for autonomous sensing of the robot's environment.

There has been a significant research interest on vision-based sensing algorithms for the mobile robot navigation task [19], [27], [31] - [46]. In particular, some research was dedicated on the application of vision systems as the sensor basis of the autonomous mobile robots engaged in coordinated behavior [2], [47] - [50]. It has been shown that there are provable visual sensing strategies advantageous over any other sensing techniques for mobile robot navigation [31]. In spite of these accumulated studies on autonomous mobile robots with visual capabilities, there is still great challenge for computer vision systems in the area since such systems require skills for the solution of complex image understanding problems. Existing algorithms are not designed with real-time performance and are too luxurious from the aspect of time consumption. The development of a vision system which can satisfy the needs of both robustness and efficiency is still very difficult [45]. Concentration of computer vision society has been accumulated on estimation of the state of the robot in the environment and the structure of the environment [46].

1.4 Formulation of Coordinated Task

Coordinated behavior among a group of autonomous mobile robots is a hot research area in various disciplines - mechatronics, computer science, robotics, etc - due to various application areas of decentralized robotic systems such as exploration, surveillance, search and rescue, mapping of unknown or partially known environments, distributed manipulation and transportation of large objects, reconnaissance, remote sensing, hazard identification and hazard removal as mentioned at the beginning of this chapter.

In this work, a generic coordinated task explained below will be used as a test bed to verify the validity of the proposed models for the coordinated motion of a group of autonomous mobile robots. The mobile robots engaged in coordinated behavior will be assumed to be nonholonomic, because autonomous nonholonomic mobile robots are low-cost, off-the-shelf and easy to find test beds in the market. A vehicle is nonholonomic if it has a certain constraint on its velocity in moving certain directions. For example, two-wheeled mobile robots are nonholonomic since they can not move sideways unless there is slip between their wheels and the ground. Two-wheeled robots and car-like vehicles are the most appealing examples.



(a) (b)

Figure 1.2: Possible sensors for mobile platforms: (a)Ultrasonic sensors (b)Onboard camera

A group of n autonomous *nonholonomic* mobile robots, namely $R_1, R_2, \ldots, R_{n-1}, R_n$, and an object, T, that will serve as a target for the group, are considered. In the sequel, R_i denotes the i^{th} robot in the group.

The coordinated task scenario and the required formations for the coordinated motion in this work can be summarized as follows:

- Starting from any initial setting of the robots and the target, $R_1, R_2, \ldots, R_{n-1}, R_n$ should form a circle of certain radius d_{targ}, with T being at the center.

- The robots should move in a coordinated manner maintaining certain mutual distances; i.e. they should approach T as a group.

- The robots should be uniformly distributed on the formation circle, with each robot maintaining a certain distance d_{near} from its closest neighbor.

- Each R_i should orient itself towards T once it achieves the requirements stated in the previous items.

A possible initial configuration for the above defined coordinated task is depicted in Fig. 1.3(a) for a group of n autonomous mobile robots. Fig. 1.3(b) on the other hand, shows the desired state of a group of five robots after the coordinated task is accomplished.

Complicated coordinated tasks can be dealt with in terms of simpler coordinated tasks that are manipulated sequentially. The instant implication of this idea is that the above scenario might serve as a general basis for more complicated coordinated tasks. For example, consider the manipulation of a heavy object, T, by a nonholonomic mobile robot group as the coordinated task. To accomplish such a coordinated task, the robots should first approach the object and grasp it in a formation as uniform as possible for mechanical equilibrium that will provide ease in lifting. Once the robots achieve the desired formation described in the above scenario, they can grasp, lift and move the object to any desired pose (location and orientation) in a coordinated manner. Another example is enclosing and catching a prisoner, T, in a surveillance area by such a nonholonomic mobile robot group. To achieve this goal, the distances d_{targ} and d_{near} should be decreased after the above explained coordinated task has been finalized.

Dealing with coordinated tasks as a sequence of simpler tasks, each of which can be considered as a "phase" of the whole task, the phenomenon of initiation of phases arises. In the first example given above, each R_i should check if the others have taken hold of the object before trying to lift it. On the contrary, the other robots can start attacking the prisoner without checking the state of the other robots in the latter scenario.