1 Introduction

1.1 Applications of UAVs

Thanks to the inherent attributes such as mobility and flexibility, unmanned aerial vehicles (UAVs), also known as aerial drones, have started to reshape our modern life. Once national legislations make laws to allow UAVs to fly autonomously, swarms of UAV will populate the sky of our cities to conduct various missions: rescue operations, surveillance, and monitoring, and also some emerging applications such as goods delivery and telecommunications. Some typical applications of UAVs are summarized in Figure 1.1.

UAVs can service humans. A typical example is that UAVs play the role of aerial base stations to provide communication service to cellular users, especially in some congested urban areas [1]. This is a promising solution to 5G and beyond-5G networks. It is also very useful in disaster areas where the communication infrastructures are down. Also, UAVs have been used to track targets, such as humans, animals, and vehicles [2], and in agriculture [3], traffic monitoring [4], architecture inspection [5], environment monitoring [6], disaster management [7]. Furthermore, UAVs can provide service to wireless sensor networks (WSNs) [8]. Working as the aerial sinks, the UAVs can collect sensory data from distributed sensor nodes. They can navigate ground robots since they may have a better view of the environment, and they can also collaborate with ground robots to execute complex tasks. Beyond those presented in Figure 1.1, package delivery is another service UAVs can provide, which also attracts great interest from both the research community [9] and logistics companies [10–14].

In addition to the sole-UAV usage, the collaboration between UAVs and ground vehicles for surveillance and parcel delivery has gained attention. A key point is using one or more UAVs to visit a given set of positions. Considering the limited capacity of the on-board battery, the flying time of a UAV is constrained. A straightforward idea is to install ground charging stations at which a UAV can recharge or replace its battery [15]. Where to deploy the ground charging stations influences

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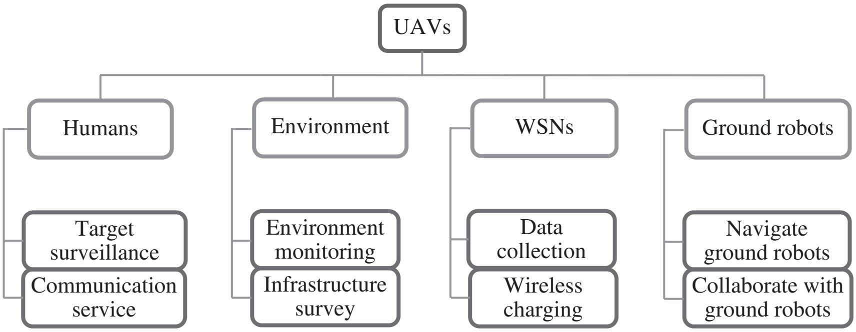

Figure 1.1 The usage of UAVs.

the coverage performance that UAVs can achieve. Given a set of ground charging stations, the review [16] focuses on the path planning problem of a UAV to visit a given set of positions successfully. Another idea is to use ground robots to function as mobile charging platforms [17–19]. Specifically, the chapter [17] considers the usage of a battery-constrained UAV and a battery-unlimited ground robot for large-scale mapping. The UAV can recharge its battery on the ground robot. While the ground robot can only move on the road network, the UAV can traverse the areas off the road network. The authors provide a strategy for the cooperation of the UAV and ground robot such that they can finish the mapping mission under the energy constraint of the UAV. The chapter [18] considers a similar scenario as [17]. The authors provide an integer program for this problem. Different from [17, 18], in [19], the UAV can travel with a ground robot together and recharge its battery during the movement. Clearly, this strategy reduces the time to finish the mission.

1.2 Problems of Autonomous Navigation and Deployment of UAVs

In order to fully reap the benefits of UAVs in the aforementioned real-life applications, some core technical challenges, including the 3D placement of multiple UAVs, the trajectory/movement design, the energy efficiency optimization. These deployment and autonomous navigation of UAVs play an extremely important role for the usage of UAVs. A typical scenario is that a team of collaborating UAVs is conducting a mission for which it is needed to determine some optimal operation status including physical positions and other application-dependent attributes such as transmission powers when UAVs serve as aerial base stations.

For a static situation, we can formulate some UAV navigation and deployment problems as optimization problems. The objective function can be application-dependent. For example, when UAVs are used to serve cellular users, a typical problem is how to deploy UAVs to cater to wireless users' instantaneous traffic demands. Existing research has investigated the trajectory planning problem for a single UAV to relay information [20] and broadcast/multicast data packets [21]. Besides the trajectory planning problem, researchers have also investigated the UAV deployment so that wireless coverage is provided to the static users in a target region, by designing the optimal operating location in 3D space [22], minimizing the number of the stop points for the UAV [23], and minimizing the total deployment time [24]. When UAVs are used to monitor ground targets, some metric describing the quality of surveillance will be regarded as the objective. Moreover, the deployment problem often comes with some constraints. An important constraint is the connectivity [25]. When multiple UAVs operate together, they need to form a connected network with some ground base station for communication. The common approach is to introduce a connectivity graph, which can restrict the relative positions of the UAVs so that a valid communication channel between a pair of UAVs is guaranteed. Another constraint is about collision avoidance. For a particular area, there may be existing some infrastructures such as buildings, which may be regarded as no-fly zones [26]. Such no-fly zones further place some constraints to the UAV deployment problem. Then, the deployment problem becomes a constrained optimization problem, and the solution to this problem is the positions of the UAVs.

For a dynamic situation, the optimal positions of UAVs will be time-varying. In this case, deployment and navigation of UAVs are coupled. The optimal positions of UAVs are computed by addressing the deployment problem, and then the UAVs are navigated from their current positions to new positions. During the navigation process, it should be guaranteed that the connectivity is maintained, UAVs do not collide with any obstacles and do not enter any no-fly zones. Model predictive control (MPC) [27] has been recognized as an important tool to address this type of constrained optimization problems. A review of recent results on deployment and navigation of teams of collaborating UAVs for surveillance can be found in the survey paper [28]. Moreover, a review of challenges and achievements in reaching full autonomy of UAVs is presented in [29]. The research monograph [30] studies various applications of UAVs for support of wireless communication networks.

Though the research community has already made a great contribution to the navigation and deployment of UAVs, many of the existing approaches suffer from the complexity for real-time implementation. Additionally, the mobility of ground targets (in wireless coverage and also surveillance applications) is generally overlooked by many research articles, based on which, the mobility of UAVs needs to be carefully considered to get a better quality of service (QoS). Motivated by such research gaps, and to facilitate the application of UAVs, navigation and deployment methods should be implemented in real-time at each UAV using local information only. This requires proposed methods be computationally efficient. Moreover, the optimality of the overall performance of the UAVs should be guaranteed. Therefore, decentralized algorithms are often needed for UAV deployment and navigation.

1.3 Overview and Organization of the Book

In this section, we briefly describe the results presented in this research monograph.

This book is problem-oriented, not technique-oriented. So each chapter is self-contained and devotes to a detailed discussion of an interesting problem that arises in the rapidly developing area of UAVs' applications. We present relevant approaches from a control system viewpoint. Thus, in Chapters 2–6, we first present system models and then formulate problems of interest, which are followed by proposed approaches to address the problems. Finally, we present computer simulation results to illustrate the effectiveness of the proposed approaches. The organization of the book is as follows.

In Chapter 2, we discuss an application of UAVs in providing cellular service as aerial base stations. We study a problem of proactive UAV deployment. The deployment of UAVs plays a key role for the quality of service in such applications. Two typical scenarios are studied. The first scenario is in urban areas, and the UAVs are deployed over streets to avoid collision with buildings. The second scenario is for disaster areas. We formulate several optimization problems to optimize the quality of service provided by the UAVs, and computationally efficient algorithms are presented to address these problems.

Chapter 3 discusses some recent developments in using UAVs to monitor ground areas and targets. Specifically, we present approaches to finding the minimum number of UAVs equipped with ground-facing video cameras and their deployment positions to fully monitor an area of interest, which can be either a flat area or an uneven area with buildings, hills, or mountains. We also present algorithms that can find the optimal positions of UAVs to survey a group of ground targets within a certain area. We develop deployment algorithms for both the 2D and 3D deployment of UAVs. Theoretical analysis on the performance of these approaches is also provided.

In Chapter 4, we discuss applications of UAVs for surveillance and monitoring of ground areas and targets, which corresponds to various practical applications including but not limited to surveillance of disaster processes such as offshore oil spills, flood and coal ash spills, and monitoring ground vehicles and pedestrians.

We present several decentralized algorithms for navigation of a team of UAVs to collaboratively conduct surveillance missions. The properties of these algorithms such as optimality are discussed.

Chapter 5 focuses on covert video surveillance using UAVs, which is a relatively new research area. Different from usual surveillance applications discussed in Chapters 3 and 4, covert surveillance requires that the intention of the UAVs is not discovered by the targets of interest. We present two approaches to this problem. The first approach is optimization-based. We present a new metric to characterize the disguising performance, which evaluates the change of the relative distance and angle between the UAV and the target. Then, we formulate an optimization problem, which jointly maximizes the disguising performance and minimizes the energy efficiency of the UAV, subject to the motion constraint of the UAV and the requirement of keeping the target within view. We present a dynamic programming method to plan the UAV's trajectory in an online manner. The second approach is a biologically inspired motion camouflage-based method. To achieve motion camouflage, the UAV always moves on the straight line segment connecting the target and a fixed reference point. A sliding mode control strategy is developed, which only takes the bearing information as input. We present extensive computer simulations to demonstrate the performance of these approaches.

In Chapter 6, we discuss the applications of UAVs in the last-mile parcel delivery. UAVs have been considered as a promising tool for future logistics industry by many companies thanks to reduced cost and increased mobility. However, one barrier is the limited flight time due to the limitation of onboard batteries. This chapter presents recent research results on using public transportation vehicles to assist UAV delivery. A particular attention is paid to path planning problems when UAVs can travel with public transportation vehicles, and several algorithms are presented to deal with these problem in different situations.

1.4 Some Other Remarks

Chapter 2 of this book studies using UAVs for wireless communication coverage, Chapters 3–5 are about using UAVs for video surveillance of ground areas and targets, and Chapter 6 concentrates on UAV assisted delivery. On the other hand, Chapters 3 and 3 of this book studies UAV deployment, Chapters 4 and 5 address UAV navigation, and Chapter 6 concentrates on UAV flight scheduling. Furthermore, Chapters 1–4 studies teams of UAVs, Chapter 5 concentrates on using a single UAV, whereas Chapter 6 studies UAVs collaborating with ground public transportation vehicles. Also, it should be pointed out that Chapters 2–5 study deterministic models that often contain large uncertainties, whereas Chapter 6 addresses both deterministic and stochastic models.

It should be pointed out that teams of collaborating autonomous UAVs guided by decentralized navigation algorithms developed in this book can be naturally viewed as networked control systems; see e.g. [31] and references therein.

The main results of this research monograph were originally published in the journal papers [32–49].

The literature in the field of autonomous UAV navigation and deployment for communication, ground surveillance, and parcel delivery is vast, and we have limited ourselves to references that we found most useful or that contain material supplementing this text. The coverage of the literature in this book is by no means complete. We apologize in advance to many authors whose valuable research contributions have not been mentioned.

In conclusion, the area of autonomous navigation and deployment of UAVs is a fascinating discipline bridging robotics, aerospace engineering, system theory, control engineering, communications, information theory, computer science, and applied mathematics. The study of decentralized UAV navigation and deployment problems represents a difficult and exciting challenge in system engineering. We hope that this research monograph will help in some small way to meet this challenge.

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