Collaborative Microdrones: Applications and Research Challenges

(Invited Paper)

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ABSTRACT

Microdrones are small-scale unmanned aerial vehicles (UAVs) carrying payloads such as cameras and sensors. Such microdrones enable us to obtain a bird's eye view of the environment which is helpful in many applications such as environmental monitoring, surveillance or disaster management.

This position paper reports on our recently launched project "collaborative microdrones" where we are developing a system for aerial imaging based on cooperating, wireless networked microdrones that can be used in disaster management applications. Several microdrones will fly in formation over the area of interest and deliver sensor data which is fused, analyzed and delivered to the user in real-time. In this paper we briefly discuss applications for UAVs, present related projects, introduce our research focus and report on preliminary results.

Categories and Subject Descriptors

C.3 [**Special-Purpose and Application-Based Systems**]: Real-time and embedded systems; I.2 [**Artificial Intelligence**]: Miscellaneous; I.4 [**Image Processing and Computer Vision**]: Miscellaneous

General Terms

microdrones, networked autonomous systems, mission planning, aerial imaging, formation flight

Keywords

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Figure 1: Small-scale microdrone with an attached camera.

1. INTRODUCTION

Advances in control engineering and material science made it possible to develop small-scale unmanned aerial vehicles (UAVs) equipped with cameras and sensors (cf. Figure 1). Such "microdrones" enable us to obtain a bird's eye view of the environment. The technology originates from military applications; recently, however, products have also been offered for the commercial market and have gained much attention. Having access to an aerial view over large areas is helpful in many applications, e.g., in disaster and law-enforcement situations, where often only incomplete and inconsistent information is available to the rescue or police team. In such situations, airborne cameras and sensors are valuable sources of information helping us to build an "overview" of the environment and to assess the current situation.

A conventional microdrone can be regarded as an autonomous system that flies in the air, senses the environment, and communicates with the ground station. It is typically controlled by a human operator using a remote control. More recent technology is equipped with Global Positioning System (GPS) based navigation and sophisticated on-board electronics that lead to high stability in the air. Such UAVs are used today for aerial imaging, police and fire rescue operations, and military missions.

Despite these advances, the use of a single microdrone has severe drawbacks, demanding for a system in which *several microdrones fly in a formation and cooperate* in order to achieve a certain mission. Potential opportunities and benefits of multiple cooperating microdrones include the following:

- A single microdrone cannot provide an overall picture of a large area due to its limited sensing range, limited speed, and limited flight time. Furthermore, it has only a limited view onto the ground due to buildings, trees, and other obstacles. A formation of microdrones can cover a much larger area. In addition, multiple views on a given scene, taken by different microdrones at the same time instant, can help to overcome the problem of occlusion.

- By intelligently analyzing different views, the image quality can be improved and even depth information can be computed, leading to a three-dimensional model of the environment.

- Last but not least, an aerial imaging system working with a multitude of microdrones can be made more robust against failures and allows a certain level of task sharing among the microdrones.

A vision for the future is to have an aerial imaging system in which microdrones will build a flight formation, fly over an area of interest, and deliver high-quality sensor information such as images or videos. These images and videos are communicated to the ground, fused, analyzed in real-time, and finally presented to the user. For instance, an overall map and detected objects of interest derived from the individual cameras' views could be given to the user.

A team at Lakeside Labs in Klagenfurt, Austria, is currently working on developing such a system of collaborative microdrones. This position paper reports on our recently launched cDrones project [1] where we develop a system for aerial imaging based on cooperating wireless networked microdrones.

The reminder of this paper is organized as follows. In Section 2 we identify application domains for UAVs and discuss the use of collaborative microdrones. Section 3 gives a short survey on projects related to UAVs. Section 4 is devoted to the cDrones project and describes the research goals of this project. Section 5 presents first results from our investigations to use microdrones for aerial mapping and Section 6 finally concludes the paper.

2. APPLICATIONS FOR UAVs

A bird's eye view is valuable in many situations such as disaster management and law-enforcement, where it is important to get a quick overview of a certain area. Currently, large helicopters or airplanes are used, but they have the drawbacks of being very expensive and, due to their high flying altitude, the spatial resolution is rather coarse. In this section we first describe a number of potential civilian application domains and then discuss how collaborative microdrones can be beneficial in these domains.

[1] `http://pervasive.uni-klu.ac.at/cDrones`

2.1 Application Domains

We identified three application domains with increasing requirements on UAV technology: (i) environmental monitoring, (ii) surveillance and law enforcement, and (iii) disaster management.

2.1.1 Environmental Monitoring

The basic idea in environmental monitoring is to deploy UAVs and take pictures of the environment. These pictures are then analyzed individually or an overall image is created by stitching together the different views. Accurate and high-resolution images taken from UAVs flying at low altitudes gives much more precise evidence compared to the pictures taken from helicopters or airplanes. An up-to-date information is important; however, it is not necessary to stitch the individual images in real-time nor to analyze the data automatically. The main motivation for using the UAVs is to cover a large area by using less resources (time, energy, ...) and they are less intrusive compared to helicopters or airplanes.

Some specific examples may include monitoring forests, agriculture fields or snow terrains. Monitoring forests allows to observe the population of trees and their state as well as to estimate potential damages. In agriculture, multiple UAVs can fly over large fields to observe crop growing or to document the damages after a thunderstorm. Analysis of the pictures taken by the UAVs while flying over snow terrains can be used to estimate avalanche risks.

Planning the flight route of the drones and optimizations can be prepared off-line. Data analysis is performed off-line after all the data has been acquired, using sophisticated and possibly time-consuming algorithms. So the main use of microdrones is to acquire images, probably with different kinds of sensors (e.g., color sensor, infrared sensor, etc.), without tight timing constraints.

2.1.2 Surveillance and Law Enforcement

Surveillance and law enforcement deals with monitoring restricted areas, private properties or public events with the main goal of detecting suspicious actions. In case of monitoring restricted areas or private properties the main issue is to detect intruders, burglars and unauthorized people.

Microdrones are used to provide an up-to-date overview of the observed area allowing security staff to assess the situation. Sensor data is analyzed in order to detect suspicious people and objects and possibly also track them. Monitoring crowds of people, e.g., people attending an open air concert or participating in a demonstration, can be supported using a fleet of drones.

In this applications it is typically not possible to plan the route beforehand but a human operator actively steers the drone. The captured images are streamed to a base station for monitoring and, if required, archiving. Image analysis is done off-line using the data from the archive, if at all. Hence, microdrones can be seen as an eye in the sky, which gives security staff and police officers a valuable overview.

2.1.3 Disaster Management

In disaster management, e.g., flooding, wildfire, earthquake, it is important to get a quick and well-founded overview of the situation since it is not possible to rely on available maps or imagery. Hence, similar to environmental monitoring, a first step is to employ a fleet of drones to map the affected area and thus provide a basis for planning further rescue activities. Additionally, sophisticated image analysis algorithms can be used on the UAVs to detect humans or certain objects and classify them. So a fleet of microdrones can be used to search for missing people and to coordinate the rescue teams.

The requirements in this application domain are much more stringent. First of all, one can not rely on fixed infrastructure such as communication infrastructure, powerful central servers and power supply. Planning the mission off-line beforehand is not feasible. So mission planning has to be done on-line and the drones have to fly the calculated routes autonomously. The whole processing of aerial mapping has tight timing constraints; it is not possible to take the images and then employ sophisticated time-consuming algorithms for off-line image stitching. Detecting and classifying objects has to be done by the UAVs and thus requires considerable processing capabilities for real-time image analysis on-board the microdrones.

2.2 Application of Collaborative Microdrones

Summarizing the application domains as discussed above, the main tasks for collaborative microdrones are as follows:

- Flying in a structured manner over a predefined area.
- Sensing the environemnt, i.e., taking pictures, recording video data, and possibly fuse it with the data from other sensors, e.g., infrared sensors and audio sensors.
- Analyzing sensor data, either off-line at the ground station or on-line, during flight, and in a collaborative manner and presenting the results to the user.
- Processing the sensor data on-board, performing object detection, classification and tracking.

We assume that a human operator specifies a set of high-level tasks via a graphical user interface. This means that the area to be observed and the quality requirements, such as the imaging resolution or update frequency, is specified by the human operator. The idea is illustrated in Figure 2. The user may designate a certain area to be observed (e.g., the one bounded by the outer red line) and specify certain requirements. In addition, a sub-area, e.g., the inner area bounded by the blue line, is marked as being of specific importance or as being an obstacle, that has to be observed with different parameters or avoided, respectively.

Using mission planning algorithms, the high-level tasks are then transformed to low-level tasks for each drone or a group of drones flying in a formation, respectively. Mission planning has to take into account the individual drone's capabilities, the dynamics of the application (e.g., drones joining or leaving the fleet due to drone's energy constraints), or changes in the high-level requirements (e.g., additional area to be observed is added during mission execution).

While in some applications it is sufficient that each drone acts individually, some applications require that two or more drones collaborate, (e.g., for having different views of a scene for 3D reconstruction, object detection or tracking) and therefore have to fly in a coordinated formation.

Figure 2: Specification of the observation area (red line) and some sub-area of special interest (blue line).

3. SELECTED RESEARCH PROJECTS

UAVs have been of great research interest over the last couple of years. In this section we present selected research projects on UAVs.

Within Framework Programme 5 of the European Commission, a thematic network called UAVNET had the goal to advance the development of civilian UAV applications. The network clustered two European projects (USICO and CAPECON). One of them focused on improving the operational capability and safety of UAVs, the other one focused on identifying and specifying civilian UAV applications and configurations. Although the projects identified the great potential of small-scale UAVs [1], these projects focused on much larger UAVs and their integration into the air traffic control system.

Another project within the Framework Programme 5 of the European Commission is COMETS [14]. It is a completed research project with a main objective to design and develop distributed control system for cooperative detection and monitoring using heterogeneous UAVs [7]. The system was tested on real forest fires [12, 11]. The project addressed mission planning and cooperative imaging, but also focused on developing and implementing control algorithms for autonomous helicopters and teleoperation tools.

In 2007, a project entitled "μDrones — Micro Drone Autonomous Navigation for Environment Sensing" has been launched within Framework Programme 6 of the European Commission. The core of this project lies in the development of software and hardware modules providing autonomy to a single small-size drone in terms of flight stability, navigation, localization, and robustness to unexpected events.

Several projects in the domain of networked UAVs are performed by the Aerospace Controls Laboratory (ACL) at MIT [9]. The research focus is on decision making under uncertainty, path planning, activity and task assignment, estimation and navigation, sensor network design, robust control, adaptive control, and model predictive control.

A similar line of research is carried out by the Aerobot BEAR project at the University of California at Berkeley. In overall, it is a long-term line of projects dating back to 1996 that is highly interdisciplinary, and involves research topics like multi-agent coordination, flight formation, bio-inspired swarming behavior, vision-based navigation, and vehicle control. The research focus has changed over years, and the current research is on flight formation, bio-inspired swarming behavior, and vision-based landing.

The Starmac project of Stanford University is composed of two phases: (i) vehicle and testbed design [8], and (ii) multi agent control demonstration. The research focus is on autonomous collision and obstacle avoidance, and task assignment formation flight, using both centralized and decentralized techniques.

A series of projects in the domain of UAV computer vision are performed by the Computer Vision Laboratory at the University of Central Florida. The output of the COCOA project [2] is a modular system capable of performing motion compensation, moving object detection, object tracking performing motion compensation, moving object detection, object tracking and indexing of videos taken from a camera mounted on a moving aerial platform (UAV). In addition, several projects in the domain of multi-sensor fusion, video registration and 3D image reconstruction are also part of the research activities of this laboratory.

The WITAS project [5] at the Linköping University focused on developing high and low level autonomy of a single large UAV. The project is interesting due to the developed high-level decision making algorithms based on vision and artificial intelligence; however, it does not focus on algorithms involving several UAVs. The goal was to use a single drone that flies over specific area and detects and tracks vehicles.

The ANSER (autonomous navigation and sensing experiment research) project was done by the Australian Center for Field Robotics. It focused on decentralized data fusion, and simultaneous localization and map building across multiple uninhabited air vehicles.

4. cDrones RESEARCH FOCUS

In the cDrones project we focus on the development of a system comprising multiple drones for disaster management. The development of such a system imposes substantial technological and scientific challenges. In this project we focus on three key research areas that form the basis of the cDrones project: (i) flight formation and networked control, (ii) mission planning, and (iii) cooperative aerial imaging.

4.1 Flight Formation and Networked Control

Microdrones should form and maintain a specific flight formation through distributed control via an ad hoc network. Such distributed control via a wireless network is a rather young research area. The key challenge here is that wireless ad hoc communication introduces non-deterministic latencies and stochastic information loss, two important aspects that the control laws have to take into account. Another research question is how to cope with failures of microdrones and drones joining a formation.

We aim to develop application-specific solutions for establishing and maintaining a desired formation flight with several microdrones. A small-scale formation with up to five microdrones should be maintained at a sufficiently accurate level, so that a desired sensor data interpretation is possible.

An overview of research issues in cooperative UAV control is given in [17]. It identifies major components of collaborative UAVs such as collision and obstacle avoidance, formation reconfiguration and high-level control. Other papers focus on low-level control engineering aspects of the UAV formation (e.g., [23, 22]).

Most current research in the field of networked control systems deals with stability and other control-related issues (e.g., [25, 20]) but almost always neglects or highly simplifies the communication topology. At the same time, the design of mobile ad hoc networks often have not considered transmitting real-time control data in a reliable manner so far.

4.2 Mission Planning

In mission planning we aim to develop methods which optimize the overall behavior of the microdrone fleet to satisfy the mission goals of our application scenario. This optimization must be carried out under time constraints and has to consider a stochastically evolving outdoor environment. In this domain we investigate how to plan a cooperative microdrone mission for a set of tasks given by a user. The system has to optimize the overall behavior of the UAV formation to meet the mission goals and to react on unpredictable dynamics of the environment.

The scientific goal is the advancement of general methods and principles for planning [6]/re-planning [21]/diagnosis [24, 13] which can be applied to other application areas. Consequently, from a scientific point of view the expected innovation is the extension of high level reasoning methods like first principle diagnosis, knowledge-based planning, plan revision, and disruption management such that the requirements of the application scenario are met. A further scientific goal is to study how flight formations can be integrated in mission planning and under which conditions flight formations improve the system behavior, e.g., by reducing computation costs of planning.

Mission planning of multiple microdrones is related to cooperative multi-agent planning which generates plans such that the resulting joint behavior achieves a predefined goal (e.g., [6, 4]). In [22] a strategy of UAV path generation for area surveillance is proposed which considers the reconfiguration of a UAV formation in case of drone losses. However, this approach does not take into account the dynamics of the environment nor changing mission goals.

4.3 Cooperative Aerial Imaging

Cooperative aerial imaging has to follow two main purposes. First, it delivers important information for flight formation and mission planning. Second, it abstracts relevant information for the user from the raw data. Hence one important research issue is how to perform feedback loops of cooperative aerial imaging for flight formation and networked control, and mission planning. Furthermore, we explore the capabilities of fusing and interpreting data from multiple sensors under tight resource limitations on-board the microdrones and the ground station in a distributed manner.

While several papers on various computer vision methods from multiple aerial cameras have been published very recently (e.g., [10, 19, 18, 3, 16, 15]), there are still many open problems in this domain. First, due to the rather low flying altitude we can not assume planar scene structures in general. Second, there are much larger variations in the ego motion of the microdrones compared to larger aircrafts typically used for aerial imaging. Finally, we must evaluate the image quality in real-time since we have to feed back this information to flight formation and mission planning.

The expected innovation of this area is to advance state-of-the-art methods for image processing and data fusion in the area of multiple airborne cameras flying at rather low altitudes with significant variations in speed and orientation. This requires a responsive compensation of the ego motion and a steady update of the relation among the cameras' fields of view. A further research goal is to evaluate the tradeoff between distributed image processing onboard of the microdrones delivering fast outputs and centralized image processing at the ground station.

5. PRELIMINARY EVALUATION RESULTS

The first phase of the project is devoted to the exploration of available UAV technologies and the assessment of UAV capabilities. We chose a commercially available drone, MD4-200, from a German company, Microdrones GmbH[2] as depicted in Figure 1. The size of this drone is about 1 m in diameter and it weights less than 1 kg. Different sensors such as accelerometers, gyroscopes, magnetometer, air pressure and temperature sensors together with advanced technology allow the drone to fly in a very stable manner. A GPS module allows to accurately hold the position and also resist wind when the drone receives no steering commands. All sensor data is recorded on the drone for post-flight analysis and selected sensor data is also transmitted to the base station. This allows to observe the drone's current state, position and orientation (also in 3D) in real-time.

A distinctive feature of this microdrone is the ability to fly a pre-defined route. On the PC a set of GPS waypoints and according altitudes can be specified and the drone then flies according to this route. Furthermore, it is possible to define certain camera actions for each waypoint (e.g., set the orientation and zoom or take a picture).

We demonstrate the imaging capabilities of our microdrone flying autonomously over the parking lot near the university at 40 m altitude, recording a video with the camera facing strictly downwards. The red line in Figure 3 illustrates the planned route over the parking lot and Figure 4 shows images taken from the drone. Note the deviation of the actual flight route (illustrated by the green line in Figure 3) compared to the planned route due to limited GPS accuracy and wind gusts. An aerial mapping from the recorded video using the COCOA framework [2] is depicted in Figure 5. The results are promising, however, there is still more work to be done.

6. CONCLUSION

UAV technology has undergone dramatic advances in recent years and will continue to do so. We will see many novel applications based on this technology in the near future. In this paper we have discussed examples for UAV applications and presented our research project on collaborative microdrones. Our future work includes establishing inter-drone communication, developing control strategies for simple flight formations, evaluating computer vision methods for aerial images, and implementing mission planning strategies for single drones in controlled environments.

Figure 3: Screenshot showing the planned route (red) and the actual flight route (green).

Figure 4: Pictures taken from the microdrone flying over a parking lot at 40 m altitude.

[2] http://www.microdrones.com/

Figure 5: Detail of a mosaic from images of the parking lot.

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