Drone networks: Communications, coordination, and sensing

Evşen Yanmaz[a], Saeed Yahyanejad[b], Bernhard Rinner[c], Hermann Hellwagner[d], Christian Bettstetter[a,c]

[a]*Lakeside Labs GmbH, Klagenfurt, Austria*
[b]*Joanneum Research, Robotics, Klagenfurt, Austria*
[c]*Alpen-Adria-Universität Klagenfurt, Institute of Networked and Embedded Systems, Klagenfurt, Austria*
[d]*Alpen-Adria-Universität Klagenfurt, Institute of Information Technology, Klagenfurt, Austria*

Abstract

Small drones are being utilized in monitoring, transport, safety and disaster management, and other domains. Envisioning that drones form autonomous networks incorporated into the air traffic, we describe a high-level architecture for the design of a collaborative aerial system consisting of drones with on-board sensors and embedded processing, coordination, and networking capabilities. We implement a multi-drone system consisting of quadcopters and demonstrate its potential in disaster assistance, search and rescue, and aerial monitoring. Furthermore, we illustrate design challenges and present potential solutions based on the lessons learned so far.

Keywords: drones, unmanned aerial vehicle networks, wireless sensor networks, vehicular communications, cooperative aerial imaging, search and rescue

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1. Introduction

Autonomous unmanned aerial vehicles (UAVs), also called drones, have received increasing interest for environmental and natural disaster monitoring, border surveillance, emergency assistance, search and rescue missions, and relay communications [1, 2, 3, 4, 5, 6, 7]. Small multicopters are of particular interest in practice due to their ease of deployment and low acquisition and maintenance costs.

Research and development in small multicopters started with addressing control issues, such as flight stability, maneuverability, and robustness, followed by designing autonomous vehicles capable of waypoint flights with minimal user intervention. With advances in technology and commercially available vehicles, the interest is shifting toward *collaborative* UAV systems. Consideration of small vehicles for the aforementioned applications naturally leads to deployment of multiple aerial vehicles that are networked. Especially, for missions that are time critical or that span a large geographical area, a single small UAV is insufficient due to its limited energy and payload. A multi-UAV system, however, is more than the sum of many single UAVs. In addition to allowing coverage of larger areas, multiple vehicles provide diversity by observing and sensing an area of interest from different points of view, which increases the reliability of the sensed data. Moreover, the inherent redundancy increases fault tolerance.

Several projects explored the design challenges of UAV systems in different applications (see our survey [6] and references therein). The general design principles of a multi-UAV system in civil applications still needs investigation and remains an open issue. In this article, we summarize some challenges for the design of a system of multiple small UAVs. These UAVs have a limited flight time, are equipped with on-board sensors and embedded processing, communicate with each other over wireless links, and have limited sensing coverage.

We identify the main building blocks of a multi-UAV system as sensing, communication, and coordination modules (in addition to the UAV platform). Our main goal is to provide an overview of the desired functionality within these design blocks and to gain insight toward a general system architecture. We envision that such an architecture can be exploited in the design of multi-UAV systems with different vehicles, applications of interest, and objectives. To illustrate the discussed principles, we introduce a representative network of collaborative UAVs and provide several real-world case studies investigating centralized and distributed approaches and the associated challenges. Specifically, we use our multi-UAV aerial monitoring system to support firefighters during a disaster, to provide large area coverage with no mission time constraints, and for search and rescue with real-time video support. We illustrate that different applications have different coordination, sensing, and communication constraints. For time-critical missions with changing objectives (e.g., search and rescue), distributed coordination and reliable sensing and networking are required. For large-area coverage, such as environmental monitoring with no time constraints, the path plan can be generated before the mission in a centralized station, and the sensed data can be processed offline, relaxing the constraints on communication. Though not investigated in this article, delivery of goods by UAVs require centralized or decentralized coordination, whereas communication and sensing need to be reliable to adapt to dynamic demands and to avoid obstacles and collision in urban environments for safe delivery. The diversity of application demands supports the analysis of multi-UAV systems from coordination, sensing, and communication viewpoints — and we envision that the lessons learned in our experiments will guide the research community toward achieving an effective multi-UAV system for a multitude of civil applications. Parts of this article have appeared in our conference paper [8].

2. System overview

Important properties of a multi-UAV system are robustness, adaptivity, resource efficiency, scalability, cooperativeness, heterogeneity, and self-configurability. To achieve these properties, the physical control of individual UAVs as well as their navigation and communication capabilities need to be integrated. Design and implementation of these functionalities, by themselves, constitute well-known research topics. Algorithms and design principles proposed by research communities in wireless ad hoc and sensor networks, robotics, and swarm intelligence provide valuable insights into one or more of these functionalities as well as combinations of them [9, 10, 11].

The past two decades saw several nonmilitary projects on UAVs (e.g., UAV-NET, COMETS, MDRONES, cDrones, OPARUS, AUGNet, RAVEN testbed, sFly, and MSUAV [6]). A classification of these projects can be made as follows: First, we can distinguish the type of vehicles used, such as helicopters, blimps, or fixed-wing UAVs. These vehicles have different sizes, payloads, or flight times, and these differences affect the network lifetime, distances that can be traveled, as well as the communication ranges. Second, a classification can be made on the focus of research, such as design of the vehicles (low-level control) or design of algorithms (path planning, networking, cooperation). Last but not least, the applications for which these networks are deployed also differ. Requirements from the applications add different constraints on the system design and they have recently been explored [6].

While these projects start from different assumptions, focus on different functionalities, and aim to address different constraints and goals, in principle, they satisfy some common design paradigms [12]. Accordingly, one can come up with an intuitive conceptual diagram that captures the essence of multi-UAV systems in the literature. Figure 1 illustrates the high level building blocks of a multi-UAV system. The *UAV platform* in this diagram refers to the used vehicles, the software and hardware associated with the low-level and high-level controls of these vehicles, and onboard processors. The *Sensing* block is responsible for observing the environment and analyzing the collected data from the environment and/or other vehicles, whereas *Communication & Networking* block enables dissemination of information between devices in the network (such as UAVs and ground control). The decision-making (e.g., path planning and task sharing) is handled by *Coordination* block, which processes feedback and constraints from the remaining building blocks. The interactions between the blocks and the required functionality from each block are dependent on the goal of the system (i.e., the application). Existing multi-UAV systems focus on the design of one or more of these blocks for different applications. For instance, MDRONES focuses on the design of autonomous small-scale UAVs (i.e., the UAV platform); COMETS consists of sensing, coordination, and communication subsystems [11], and sFly focuses on a combination of UAV platforms, sensing, and coordination blocks.

This abstract representation simplifies the design considerations for multi-UAV systems and needs to be

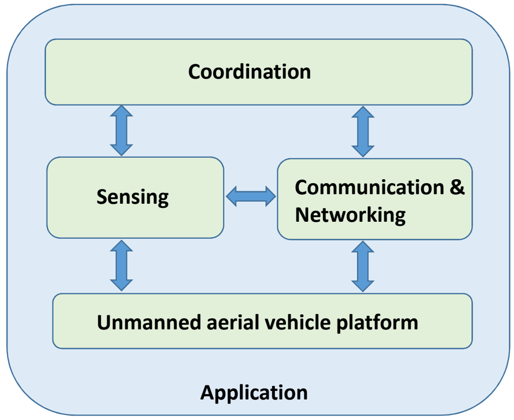

Figure 1: Multi-UAV system design blocks

refined further to come up with specific design paradigms. In principle, one can treat these blocks independently when engineering a multi-UAV system and address the challenges imposed by each block decoupled from the others. This intuitive and simple decoupling approach allows importing algorithms from the corresponding research community. A more interesting albeit challenging approach is to deploy an integrated design that takes into account interactions and influences between blocks. The method of integrating these blocks, designing the necessary interaction and feedback mechanisms, and engineering an *ideal team* of multiple UAVs are important issues to be addressed.

3. System architecture

A multi-UAV system can operate in a centralized or decentralized manner. In a *centralized* system, an entity on the ground collects information, makes decisions for vehicles, and updates the mission or tasks. In a *decentralized* system, the UAVs need to explicitly cooperate on different levels to achieve the system goals and exchange information to share tasks and make collective decisions. Independent of whether operation is centralized or decentralized, what makes a group of single UAVs into a *multi-UAV system* is the implicit or explicit *cooperation* among the vehicles. The UAVs need to

- *observe* the environment,
- evaluate their own observations and information received from other UAVs, and *reason* from them, and
- *act* in an effective way.

Reasoning can be done at the centralized control entity or on-board the UAVs with full or partial information. The possible *actions* are determined by the capabilities of the UAVs and the goal of the multi-UAV system.

In the following, we relate the sensing, communication&networking, and coordination blocks in a multi-UAV system to the observe-reason-act (ORA) cycle (similar to the OODA loop of military operations [13]) and summarize desired functionality and associated tasks in these building blocks. We do not characterize the UAV platform and assume that system can contain a heterogeneous set of small-scale UAVs (such as a multi-rotor capable of autonomous flight with limited payload, flight time, and computational power).

3.1. Sensing

The *sensing* block acts as eyes in the air. Reliable and accurate sensed data is critical for meeting the goals of the mission. Depending on the application, a variety of sensors may be used on-board the UAVs. While cameras as passive sensors are commonly used for the purpose of aerial monitoring, active sensors (such as laser-scanners, ultrasonic, wireless transmitter-receiver pairs) can also be used for *observation*. These sensors need to be lightweight with an easily accessible interface for communication and at the same time be able to provide sufficient quality of sensory data to satisfy mission requirements. Some specific issues that need to be addressed in this block are:

- *Robust sensing:* The capabilities and characteristics of sensors may affect the planning, coordination, and communication architecture. For instance, the UAV waypoints are planned considering the field of view of the sensors on-board. However, a UAV may tilt due to the flying dynamics or wind. In such cases, the tilt-angle needs to be taken into account for calculation of the field of view. Some UAV manufacturers mount the sensors on active suspensions to compensate for the tilting effect, provided that the payload limit is not reached.

- *Sensor fusion:* A UAV is commonly equipped with a diverse set of sensors such as GPS, gyroscope, accelerometer, and barometer. Therefore, a robust method for data fusion from multiple heterogeneous sensors is required. These sensory-data need to be further synchronized and analyzed to achieve information fusion and higher level goals, such as coordination and obstacle/collision avoidance.

3.2. Communication

The *communication&networking* block is responsible for the information flow in the ORA cycle. This block needs to be robust against uncertainties in the environment and quickly adapt to changes in the network topology.

Communication is not only imperative for disseminating observations, tasks, and control information, but it is needed to coordinate the vehicles more effectively toward a global goal, such as monitoring a given area or detecting events in the shortest time, which are especially important in disaster situations. Some specific issues that need to be addressed in this block are as follows:

- *Connectivity*: If communication infrastructure is lacking, the use of UAVs as relays between disconnected ground stations will become imperative. UAVs have limited communication ranges, are highly mobile, and have scarce energy resources (i.e., the UAVs can leave and enter the system based on their battery levels). This block has to maintain connectivity, and the used networking and scheduling protocols need to adapt to the dynamic environment.

- *Routing and scheduling*: Beyond maintaining connectivity and meeting quality of service (QoS) requirements, protocols that can handle or, more desirably, that incorporate three-dimensional controlled mobility need to be designed.

- *Communication link models*: Multicopters have specific layouts and constraints different from fixed-wing UAVs. Models that capture the characteristics of UAV-UAV and UAV-ground links are needed.

- *Data transmission*: Transmission of the payload data, e.g., control information, sensor readings, images, and videos, has to be performed such that the QoS requirements (data rate, delay/latency, reliability) of the application are met under varying network conditions. This may include adaptation of the payload data, e.g., capturing/transcoding an image/video in/to lower spatial resolution or using scalable encoding such as JPEG2000, in case of tight constraints imposed by the network.

3.3. Coordination

The *coordination* block is the reasoning and decision-making entity, which is responsible for using observations (own and from other UAVs), mission requirements, and system constraints to organize the UAVs. In a nutshell, it needs to compute the trajectories of the UAVs and make decisions on how to allocate tasks to achieve team behavior. Coordination can mean achieving and sustaining rigid formations or can be task distribution among vehicles in a self-organizing manner. Similarly, it can be done at a local or global level, depending on the mission and capabilities of the vehicles. Scalability and heterogeneity are also desired in a multi-UAV system, since a large number of vehicles with different capabilities are expected. Therefore, the coordination block needs to handle growing numbers of heterogeneous UAVs, tasks, and possibly mission areas. Some specific issues that need to be addressed within this block are:

- *Task allocation*: Reasoning and decision making is needed to optimally distribute tasks to individual UAVs or groups of UAVs that can handle uncertain or incomplete information and dynamic missions. Mechanisms to define and adapt tasks to the mission requirements or vehicle capabilities need to be designed.

- *Path planning*: There are several path planning strategies for ground robots and trajectory designs for formations of robots. More task-optimized, communication-aware, three-dimensional path planning methods are desired for multi-UAV systems that can handle scarce energy resources and heterogeneous vehicles.

This general overview and the representation in Fig. 1 can be seen as an initial abstraction of the components of a multi-UAV system and can provide some guidelines in the design of multi-UAV systems with different capabilities and with different constraints imposed by different applications. In the following, we refine this abstract representation and implement a collaborative multi-UAV system that can be deployed for various applications.

4. Collaborative drone network

In the following, we present the details of our collaborative drone system and summarize our solutions to some of the challenges mentioned in Section 3. Keeping the abstract representation in Fig. 1 in mind, we define the interactions between the design blocks and the required functionality according to the constraints of the application and vehicles at hand. Specifically, we focus on the design of sensing, communication, and coordination blocks of the general architecture, where commercial quadcopters are used as the UAV platform.

The objective of our system is to monitor a certain area in a given time period and with a given update frequency to assist rescue personnel in a disaster situation. It is designed to (i) capture aerial images and provide an overview image of the monitored area, and (ii) detect and document the status of a target in *real-time*. Figure 2 depicts the high-level architecture. The basic operation starts with a user-defined task description, which is used to compute routes for the individual UAVs. For the area monitoring application, the UAVs fly over the area of interest and acquire images. The images are sent to the ground station and become mosaicked to a large overview image. For the search and rescue application (SAR), the UAVs search the object of interest in a given area. Once the object is detected, they reposition themselves, forming a communication relay chain, to deliver real-time video of the target to the ground station. The high-level modules in this architecture are: (i) the user interface; (ii) the ground station comprising mission control, mission planning, and sensor data analysis; i.e., *coordination*; (iii) a *communication* infrastructure; and (iv) the *UAVs* with their on-board processing and *sensing* capabilities.

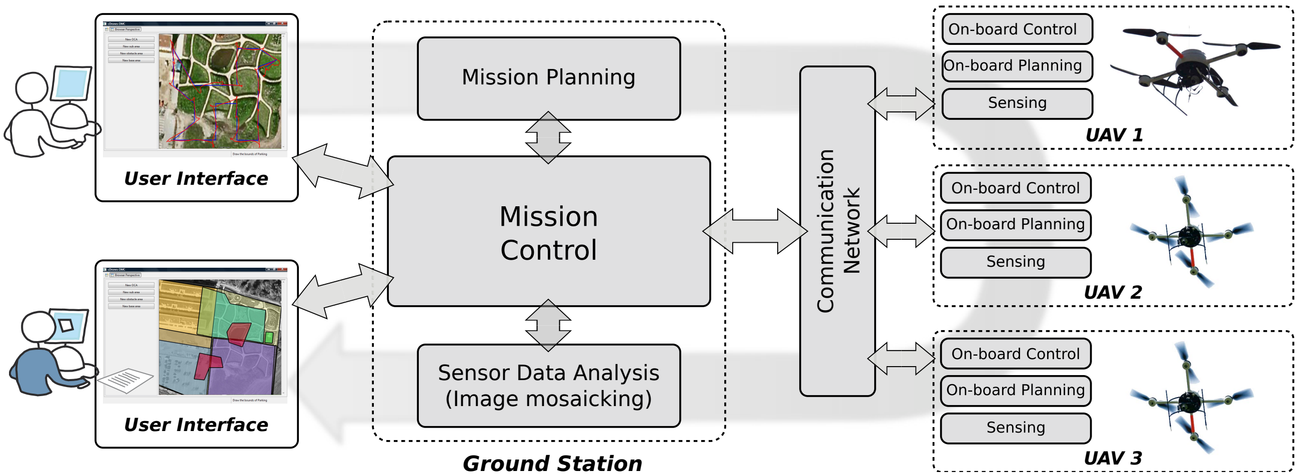

Figure 2: System architecture: Double-headed arrows indicate interactions between individual modules while the shaded arrow in the background indicates the basic operation flow.

The interactions between the design blocks (i.e., the aforementioned high-level modules) are indicated by double-headed arrows in Fig. 2. In our work, we implement and analyze different forms of interactions, depending on the application constraints. For instance, the sensing and coordination blocks are linked through sensing capabilities, desired sensor coverage, and resource limitations of the UAVs (e.g., flight time) [14]. The sensor data to be delivered impacts the communication&networking block during scheduling of transmissions [15]. We also consider alternative levels of interactions between coordination and communication&networking blocks, where we have the option of centralized coordination with no interaction or decentralized coordination with communication-dependent UAV motion [16, 14].

We support different types of UAVs provided they have some minimum functionality, such as autonomous flight and means to specify the navigation waypoints. The computed routes are given in a platform-independent format and the UAVs' on-board control translates these generic commands into the UAV-specific low-level commands. We use a heterogeneous set of UAVs including Microdrone MD4-200, AscTec Pelican quadcopters, and AscTec Firefly hexacopter (Figure 3). With more UAVs, the complexity for coordination and planning also

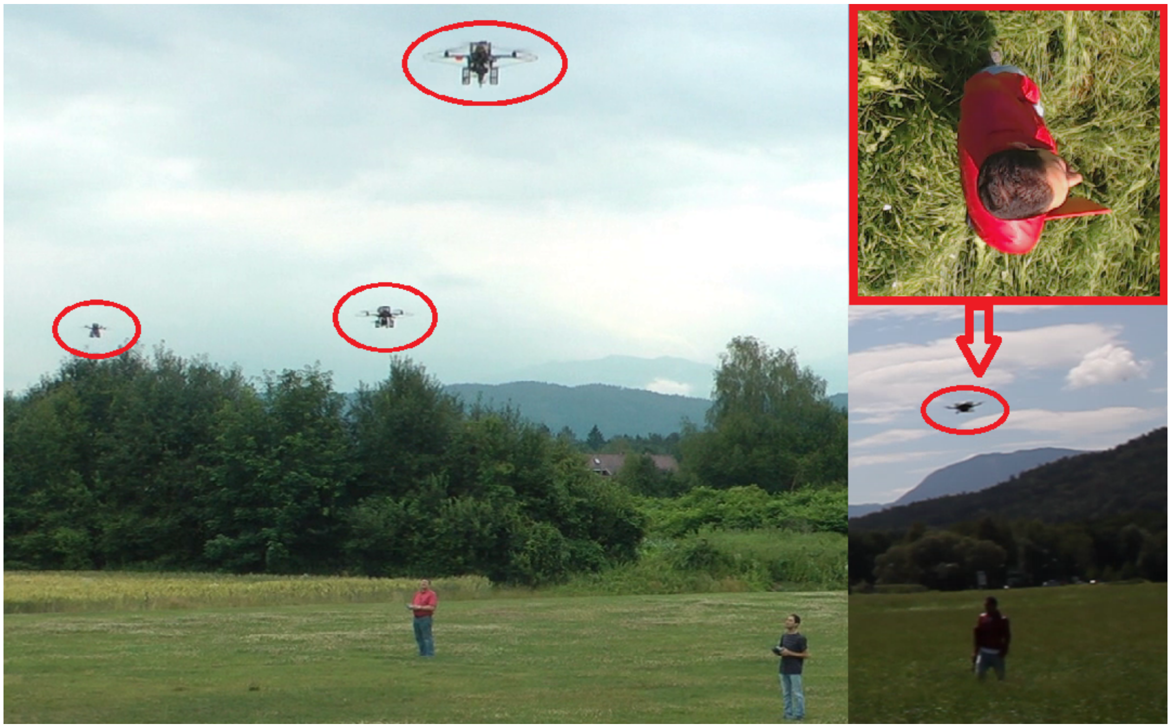

Figure 3: AscTec Pelican and Firefly UAVs in missions at the University of Klagenfurt campus.

increases. Thus, we need a robust distributed architecture for software development which provides a convenient framework for low-level device control and message passing between the nodes. The Robot Operating System (ROS) has been exploited in our system for this purpose. Using the UAVs with a processing capability on-board and equipped with ROS, each entity (UAV or base station) is able to obtain the current status from or send commands to other entities conveniently. We consider both centralized and decentralized coordination (planning and sensor analysis) and communication modules. In the decentralized case, planning functionality is migrated from the ground station to the UAVs.

4.1. User interface

The *User Interface* has two main purposes. First, it allows the user to define the high-level tasks to be accomplished by sketching the area to be monitored on a digital map. Additionally, the user can define certain properties such as the required image resolution or update intervals (cf. Figure 4). Second, it provides the user with the generated mosaicked image with the current positions of the UAVs. During mission execution, the user can change the tasks as needed.

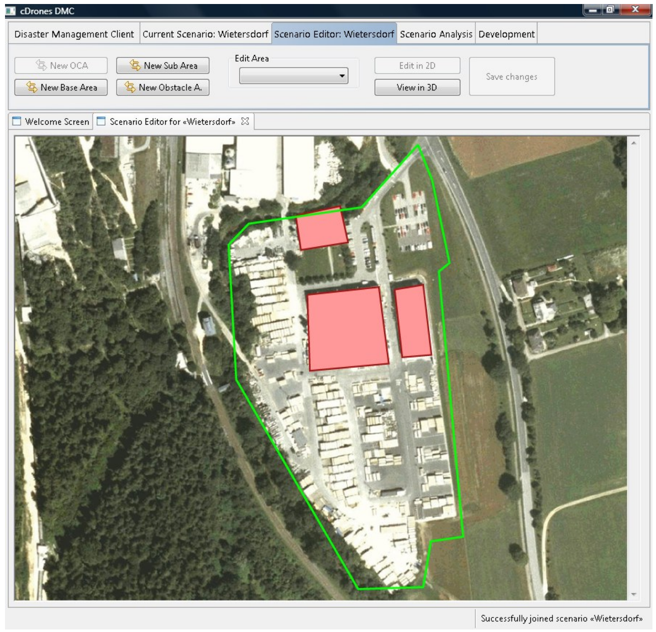

Figure 4: User interface showing the observation area (green polygon) and forbidden areas (red polygons) defined by the user on a digital map [Map data: Google].

4.2. Sensing

For the design of this block, we consider the needs of the applications at hand and aim to address the challenges imposed by the limited resources (e.g., payload, computational power) available on-board the UAVs.

Before or during the mission, the flight routes (sequence of waypoints) are sent to the UAV's *On-board Control*. The on-board control is not only responsible for the low-level control to stabilize the UAV's altitude, but also to navigate efficiently to the computed waypoints. The *Sensing* module is responsible for capturing images and pre-processing the image data on-board before transmission to the ground station. Pre-processing includes feature extraction, annotation with meta-data, quality checks (to delete blurred images), and multi-resolution encoding.

Depending on the application, different types of cameras are used for sensing. We use visual cameras for capturing images during daylight, while a thermal camera may be used for night vision, seeing through smoke or fog, vegetation monitoring, fire and heat detection using infrared patterns, etc. If the captured images are going to be used for further processing (such as object detection, image analysis, 3D reconstruction, and image mosaicking), they will be transferred to the base station [17]. Otherwise, if all the images are not necessary to be transferred, they can be processed on-board to extract a specific pattern or feature and then the UAV reacts accordingly and/or starts streaming the captured images from a target area [18].

Small-scale UAVs have limited resources, and it is critical to assign these resources carefully. We use image compression for reducing the size of the data before transferring them. Using an image pyramid is another way to save data transmission load and processing power. Very often, images with low resolution and quality are processed or transferred first; we proceed to higher quality later when resources become available.

4.3. Communication

Our research regarding the *communication&networking* block focuses on achieving and maintaining connectivity, analysis of air-air and air-ground channels via real-world tests, determining the limitations of existing wireless communication technologies, efficient data transmission, and analysis of communication demands from an application viewpoint.

To establish a reliable multi-UAV system, it is necessary to consider the demands posed by networking of the UAVs and base stations. An aerial network with three dimensional mobility benefits from antennas with nearly isotropic radiation intensity patterns. Furthermore, to enable distributed online decision making, it is necessary to have real-time communication. In adaptive application scenarios, like in one of our use cases (SAR), where the mission tasks vary over time, such communication may be required to disseminate information (e.g., detection message) and tasks (e.g., traffic generation and information relaying). Furthermore, SAR is a time-critical application where continuous connectivity to ground personnel is mandatory. Thus, persistent network connectivity is desirable to propagate information efficiently.

Many wireless technologies including Zigbee, Wi-Fi, WiMAX, and LTE have been tested for aerial networks (see [6] for a comparison and discussion of suitability of these technologies to different UAV applications.) Our system does not impose special requirements on the communication infrastructure. Therefore, as a first step, we have used standard IEEE 802.11(a/n/ac) wireless LAN on-board our UAVs in infrastructure and mesh modes. We have tested methods to improve the wireless links for ground-UAV and UAV-UAV communication in terms of throughput and radio transmission range [19, 20, 21]. We have introduced an antenna structure in the shape of a horizontal equilateral triangle, which uses three Motorola ML-5299-APA1-01R dipole antennas, to provide nearly isotropic coverage [19]. This antenna structure is mounted at the base station (see Figure 5) and all UAVs. The requirement for peer-to-peer connectivity between the devices is addressed using an ad-hoc network. An IEEE 802.11s mesh is used for this purpose. A performance analysis has been performed in [20], comparing the network characteristics of a multi-hop ad-hoc network for infrastructure and mesh modes, to examine the

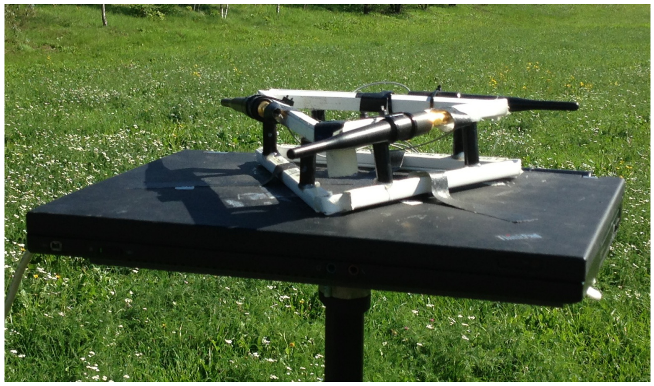

Figure 5: Base station with triangular antenna setup.

strengths and weaknesses of each mode. The system exploits relaying to establish connectivity for out-of-range nodes.

Furthermore, we have compared the networking performance of IEEE 802.11a, 11n, and 11ac radios [21]. Results are reported in Section 5. It has been shown that higher throughput over longer distances can be achieved using commercially available 802.11n modules employing the three-antenna structure on the quadcopter platforms. A newer technology 802.11ac has also been tested in [21]. While the laboratory measurements show significant improvement over 802.11n, our outdoor tests result in similar throughput for 802.11n and 802.11ac for distances over 100 m.

Once we have determined the limitations of the wireless channel in an aerial network, we have shifted our focus to communication demands of a multi-UAV system. The demands on network connectivity depend on the application [12, 6]. Hence, to determine QoS demands from an aerial network, we have taken an application-driven approach [12] and have identified the building blocks of a multi-UAV system in terms of communication need of the functionality demanded by a given application. We have given some rules of thumb for different application classes, presented a comparison of networking performance from real world tests in the literature, and provided insight into the future of aerial networks. We have further analyzed the characteristics of aerial networks, the quantitative and qualitative demands, and compared the capabilities of wireless technologies [6].

4.4. Coordination

The *coordination* block plans the flight routes of the UAVs, adapting to the needs of the application of interest (i.e., area coverage and SAR in this paper). Our research focuses on the design of path planning and task allocation strategies, taking into account sensing and communication constraints (e.g., sensing uncertainty, limited communication bandwidth).

The *coordination* contains three main components. *Mission Control* is the core module of our system. It takes the user's input and dispatches it to the other components. The *Mission Planning* component breaks down the high-level tasks to flight routes for individual UAVs. A flight route contains a sequence of points to visit in world coordinates (GPS coordinates) and certain actions for each waypoint (e.g., take a picture). Finally, the *Sensor Data Analysis* component mosaics the images from the UAVs into a single large overview image, which is then presented to the user. Since mosaicking is a computationally intensive process, we exploit an incremental approach that promptly shows an overview image to the user while the UAVs are still executing their mission [17].

We have developed both centralized and distributed coordination (mission planning) strategies to handle static and dynamic environments (for details of our strategies, the readers are referred to [16, 14]). Similar to communication and networking demands, coordination of a multi-UAV system, the decision-making process, and the level of information exchange among devices depend on the tasks related to each application. For the area coverage application, we consider pre-defined UAV paths generated at the ground station [14]. To this end, the area of interest is divided into cells, corresponding to picture points, such that the number of pictures to cover the area is minimized and the quality requirements for image stitching are satisfied. Then, using a multiple traveling salesman problem approach, shortest paths over the picture points are generated taking into account the number of vehicles and flight-time limitations. If the paths need to be updated during the mission, the new paths are generated at the ground station and delivered to the UAVs in a centralized manner. An analysis of our proposed pre-defined and distributed coordination approaches for the area coverage application in terms of mission time and planning complexity can be found in [16].

For the SAR application, on the other hand, tasks of the UAVs might change during the mission, e.g., due to new information sensed by the UAVs. Therefore, a pre-defined path plan is not suitable. To this end, in [22], we propose several cooperative search strategies, where our objective is to minimize the search time subject to sensing and communication constraints. We incorporate two dimensions, namely, information merging and decision making, into the coordination process, each of which can be distributed or centralized. Our analysis shows that depending on the availability of information and capability of making decisions, the UAVs can search an area more efficiently, if both information merging and decision making processes are distributed. In addition to our theoretical analysis of coordination algorithms in [22], we have also implemented and demonstrated autonomous coordination for the SAR use case, which is presented in the next section [18].

5. Case studies and lessons learned

We demonstrated our system in several real-world applications, including assistance during a disaster, documenting the progress of a large construction site, and search and rescue. These studies represent different UAV applications with different demands and constraints. For the construction site monitoring, real-time data exchange is not critical, whereas the quality of the generated end image needs to be high. Therefore, centralized coordination with pre-defined paths is sufficient. Since there is no time-criticality, the UAVs can fly multiple rounds to cover the whole area. On the other hand, for the disaster management and SAR applications, the progress of the event and the status of the target needs to be delivered to the ground station continuously. For these case studies, we use centralized and distributed coordination, respectively. The UAVs fly pre-defined paths and deliver images to the ground station for the disaster management case, which is an area coverage application. In the SAR case, the UAVs reposition themselves in a distributed manner to form a communication relay chain, once the target is detected.

5.1. Disaster management: Aerial overview for firefighters

We took part in a county fire service drill with more than 300 firefighters practicing different scenarios. In total, we did five flights over a period of about three hours. The accident scenario was a leaking railroad car with hazardous goods. Our task was twofold: (i) to build an up-to-date overview image of the affected area, which allows the officers in charge to assess the situation and allocate field personnel; and (ii) to frequently update the overview image of the area during the mission to keep track of ongoing ground activities.

We have followed an approach with central control. The routes of all UAVs are pre-computed on the ground station and then sent to the UAVs' on-board control for execution. The sensor data analysis, i.e., the overview image mosaicking, is done at the ground station. Figure 4 shows a screen capture of the user interface with the area of interest (green polygon) and three forbidden areas (red polygons). In this case, the forbidden areas are large buildings, which are not of interest. However, the forbidden areas can also mark obstacles or potentially dangerous areas to be avoided. Three UAVs were used to cover the whole area in a given flight time (approx. 15 min). Figure 6 depicts the computed plan using an integer linear programming strategy outlined in Section 4.4 for the three UAVs (red, blue, and green routes), the circles along the route indicate the positions where pictures are taken. In total, 187 pictures are needed to cover the area of interest (approx. 55 000 m^2) using a camera

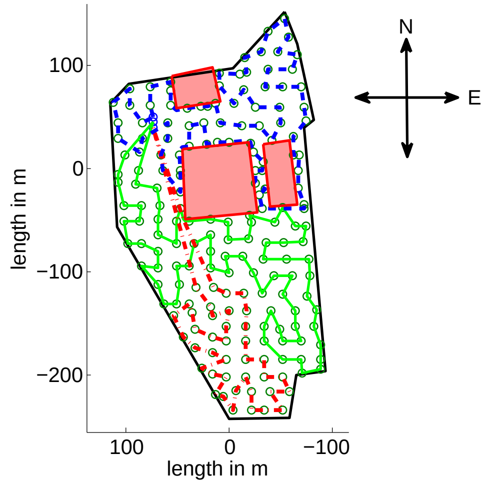

Figure 6: Mission plan for three UAVs to cover the area of interest

with a focal length of 28 mm and a flight altitude of 40 m. We have used an average overlap of 50 % between neighboring images to create enough redundancy in case some images cannot be used because of low quality and to compute an overview image that meets the quality requirements imposed by the application. The lengths of the three routes are between 950 m and 1 350 m.

One of the challenges we have faced is transmitting the images from the UAVs to the ground station over the 802.11a wireless channel. For this aerial monitoring case study, the required throughput to transmit the images (each of which is about 3 MB in size, captured every 10-15 s) from one UAV is about 2.5 Mbps. The throughput that can be provided over various 802.11 links has been measured in field tests at the University of Klagenfurt (see Table 1). Observe that these results are encouraging the use of UAVs as communication relays between otherwise disconnected ground nodes for this disaster scenario. We use JPEG2000 multi-resolution image compression and apply a scheduled transmission scheme that transmits low-resolution image layers first and additional image layers for higher resolution images as the channel permits [15]. This enables us to immediately present low-resolution images to the user while the UAVs are still on their mission and improve the image quality over time when better quality image layers become available. Figure 7 depicts a part of the overview image computed from a set of about 40 pictures. It covers the main area of activity during this fire service drill.

5.2. Construction site monitoring

We used our system also in other applications such as monitoring large areas, where fast mission execution is not of primary concern. However, the mission had to be repeatable over a longer period of time (e.g., once

Figure 7: Part of the overview image stitched from approx. 40 pictures taken during the firefighter's practice along with the UAV's trajectory (red path).

Table 1: Throughput measurements of aerial Wi-Fi networks for line-of-sight links including air-air (A2A), air-ground (A2G) and ground-air (G2A)

Technology	Link	Topology	Throughput
802.11a (P_{tx} = 20dBm)	A2G, G2A, A2A	single-hop single-hop	UDP: 14 Mbps (350 m), 29 Mbps (50 m) [19] TCP: 10 Mbps (500 m), 17 Mbps (100 m) [20]
802.11n (P_{tx} = 12dBm)	A2G, G2A,	single-hop	TCP: 10 Mbps (500 m), 100 Mbps (100 m) [21]
802.11ac(P_{tx} = 10dBm)	A2G, G2A,	single-hop	TCP: 5 Mbps (300 m), 220 Mbps (50 m) [21]
802.11a + 802.11s (P_{tx} = 12dBm) (fixed PHY rate: 36 Mbps)	A2G A2A–A2G	multi-hop multi-hop	1-hop: 5 Mbps (300 m) [20] 2-hop: 8 Mbps (300 m, infrastructure mode) 2-hop: 5 Mbps (300 m, mesh mode)

every week) and the resulting overview image had to be spatially accurate. The goal of the second case study was to document the progress of building a bicycle path as part of a larger construction site.

The property developer specified the area of the bicycle path on the construction plan. The area to cover was approximately 1 500 m by 70 m large. Based on the construction plan, we computed a mission plan for three UAVs similar to the first case study. To cover the whole area with sufficient overlap, about 120 pictures are required. The route length for every UAV is about 1.3 km and the flight time is about 12 min.

Figure 8 shows the mosaicked overview picture on top of the construction plan. We illustrate different levels of detail: the whole image is shown in the bottom; a more detailed view of the rightmost part of the overview picture is in the middle; and, finally, the top left corner shows a closeup of the area marked with the red rectangle. The blue polygon denotes the area to cover. Image blending is not applied, so that the individual images can be seen.

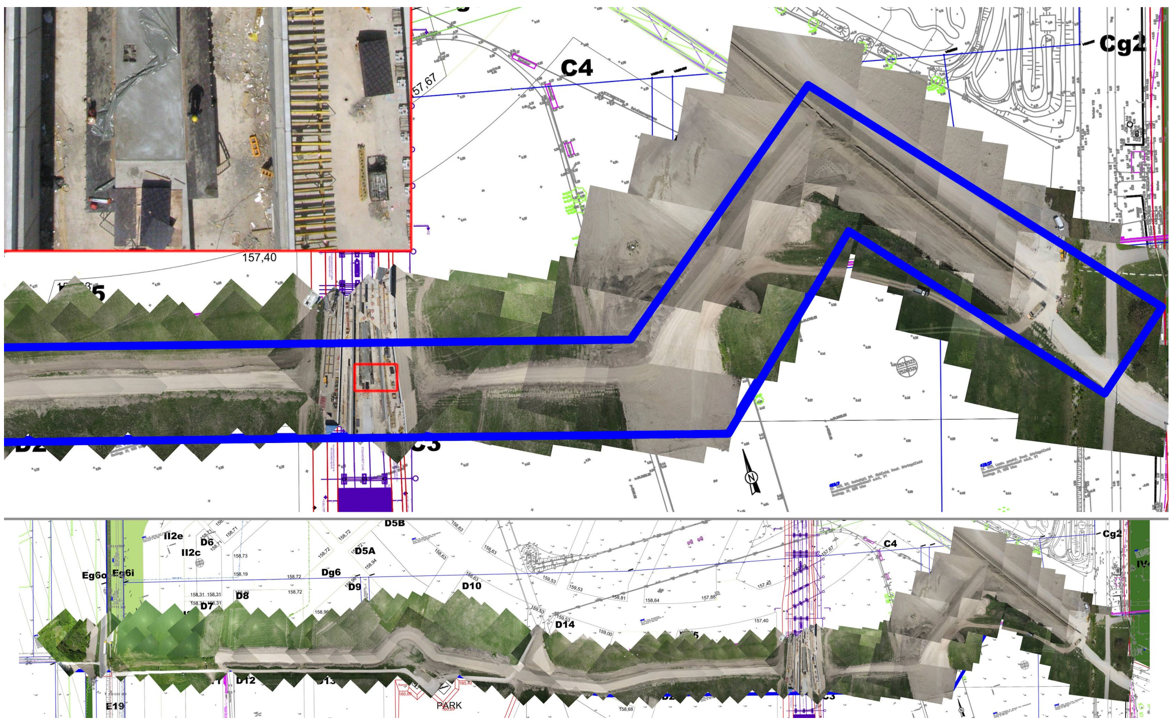

Figure 8: Final overview image of the bicycle path (bottom) with a more detailed view of a part of the overview image (middle) and a closeup (top left corner).

The large extent of the area in one direction poses additional challenges when mosaicking the images, since images overlap only in one direction. Small errors in mosaicking two individual pictures propagate to the subsequent images and may result in a severely bended overview image. With our incremental mosaicking approach [23], we could compute a geometrically accurate overview picture, which is especially important in applications where the progress needs to be tracked accurately.

5.3. *Search and rescue*

In this demonstration, our aim was to set up a search and rescue (SAR) mission by using an autonomous multi-UAV system. The goal of an SAR mission is to locate a target such as a person or an object of interest using on-board sensors and, if necessary, stream a video from the target area to the base station. The following phases are performed in the mission:

1. *Pre-planning*: Like in previous case studies, initially, we define a search region at the base station and calculate a pre-planned path for each UAV to fly, using the multiple traveling salesman strategy outlined in Section 4.4.
2. *Searching*: All UAVs take off and follow their assigned paths while images are captured and analyzed on-board.
3. *Detection*: Depending on application, dominant image background (e.g., grass, snow, water), and knowledge of the target (human, object, pattern, color) we adapt our detection algorithm. In case of known objects or patterns, we use conventional feature-based blob detectors. We also have implemented a simple color-based blob detector for unknown shapes yet known color (e.g., in Figure 3 a person with a red jacket is detected). If the expected pattern or object is found, the detecting UAV commands all other UAVs to stop and get ready for a new formation.
4. *Re-positioning*: All UAVs follow their new command to re-position and fly to their relay positions. The new positions are computed at the base station such that a multi-hop link between the detecting UAV and the base station can be established.
5. *Streaming*: Captured images of the target area are transferred to the base station through the relaying UAVs until a return command from the base is received.

In this scenario, unlike the previous case studies, we may plan or re-plan the mission even during mission execution. Hence, navigation and collision avoidance become more challenging. The decision-making for tasks such as planning, navigation, collision avoidance, detection, and streaming may be done in a distributed, centralized, or an autonomous way. Table 2 shows the level of autonomy and decision-making for each task in different phases. For instance, during the Detection phase, the planning can be done either by the detecting UAV (noted as DU) as a centralized decision, or all other UAVs can come to a consensus in a distributed way [18].

In this case study, we also performed experiments using payload data (video) adaptation depending on the dynamic constraints imposed by the network. Since the network throughput can vary widely, we developed, prototyped, and evaluated an approach to adapt (reduce or increase) the spatial resolution and, hence, data rate of a video captured by a drone depending on the current quality of the link from the drone to the ground station. Real-world flight tests indicate that this adaptation process can frequently avoid the complete loss of video pictures which happens without adaptation, of course at the cost of temporarily reduced video quality [24].

Table 2: Types of decision-making such as Distributed (D), Centralized (C), and Autonomous (A) for each task are shown in different phases of the SAR mission. Centralized tasks are coordinated either by the base station (BS) or by the detecting UAV (DU).

Tasks / Demo phases	Planning	Navigation	Collision Avoidance	Detection	Streaming
1: Pre-planning	C (BS)	-	-	-	-
2: Searching	-	A	D	A	A
3: Detection	C (DU) / D	-	-	-	A
4: Re-positioning	-	A	D	-	A
5: Streaming	-	-	-	-	C (DU) / D

5.4. Lessons learned

In the following, we elaborate on the performance of the overall system and the individual functional blocks. We summarize our observations from our experiments and discuss the implications of our design choices.

- The *User Interface* (shown in Fig. 4) is useful and efficient in defining the tasks. The observation area and forbidden areas can be marked in less than two minutes. The capability to view images as they become available is valuable to users for assessing the situation and re-planning if necessary.

- For missions with fixed goals, the *Mission Planning* component generates a (pre-)plan taking into account the user input, available resources, and mission requirements. This phase takes about one minute. A sequence of waypoints with corresponding GPS coordinates and a list of actions are then uploaded to the UAVs. The UAVs are ready for takeoff in about five minutes (including acquiring the current GPS position). For the area coverage and SAR applications, the time needed to cover the whole area and the time to detect a target, respectively, could be reduced. This reduction depends on the desired image quality for the overview picture or the required image quality for the object detection algorithms. It can be achieved, e.g., by choosing less overlap between neighboring pictures and/or using a higher flight altitude.

- The use of ROS facilitates the software development for complex projects with multiple distributed nodes. This way, we can easily extend our structure to a larger number of UAVs and base stations. Every authorized entity equipped with ROS can join the network and publish or subscribe to different predefined message types on demand. These messages include the images, flying altitude, GPS position, and other telemetry data. However, since ROS is not a real-time system inherently, time synchronization may be challenging unless a real-time implementation (e.g., ROS code extension or using ROS2) is integrated. In addition, the inherent structure of ROS helps to reduce the load in data intensive networks by using functionalities such as remote procedure call, distributed message passing, distributed data processing, and distributed decision making. ROS also has a huge database of open-source software packages (e.g., robot control, sensor/camera driver and acquisition, image processing tools) with active support for developers.

- To compute overview images of high quality, it is important to choose the appropriate equipment. High quality cameras are too heavy for small-scale UAVs. Lightweight cameras, on the other hand, are not as well-developed and require setting parameters such as focus, exposure time, and white balance. Working with dozens of high resolution images requires significant amounts of memory, computing power, and data rate. When mosaicking an overview image of large and structured areas taken from low altitude, it is important to minimize the stitching errors for every single image. State-of-the-art mosaicking tools fail in such cases, because their optimization goal is a visually appealing panorama taken from a single viewpoint. In our mosaicking approach, spatial accuracy is more desirable than the visual appearance. In addition, performing global optimization is also not possible if there is no closed loop in the set of image sequences (e.g., way-points that images are taken are along a straight line). More complex mosaicking methods and point-cloud/3D model construction will also fail in absence of sufficient overlap between images, since by definition they need at least two view-points looking to the same area.

- While for area coverage missions, image processing such as mosaicking can be done offline on the ground after the flights are finalized, in SAR missions, we need to process the image and search for a specific target in the scene as soon as possible. Therefore, performing object detection or pattern recognition is more useful than image mosaicking. In our case study mentioned in Section 5.3, we have integrated a simple red-color blob detection algorithm on-board each UAV, as shown in Figure 3, to test our system. Our experimental results with more complex patterns such as texts (see Figure 9) have not been as successful. Although each letter was printed on a separate A4 paper sheet, the text resolution was not sufficient for a robust optical text recognition. To solve the problem, we needed either to use a higher resolution camera, which is heavier and needs more on-board data processing, or fly at lower altitudes which increases the whole mission time due to a smaller field of view and consequently reduced coverage.

Figure 9: A sample text pattern captured by a UAV.

- The multi-UAV system has to deal with *omni-present resource limitations*. Small-scale platforms impose strong resource limitations on several dimensions. The available on-board energy directly influences the total flight time but also affects the payload and possible flight behavior and flight stability, especially in windy conditions. Limited sensing, processing, and communication performance impede sophisticated on-board reasoning, such as performing real-time collision avoidance or online data analysis. Compensating a resource deficiency in one dimension often impairs another resource dimension. For example, flying at lower speed typically improves the image sensing but reduces the covered area.

- While our centralized planning approach allows for re-planning, a more adaptive coordination, where the UAVs decide their tasks on their own, would be beneficial especially in case of dynamic environments. For instance, if the goal is beyond getting an overview image, e.g., tracking changes and dynamic events, like in SAR, the trajectories cannot be determined beforehand. A distributed and adaptive coordination can also give further capabilities and response options in a disaster management scenario. For instance, the UAVs can be used to track the boundary of the hazardous materials or guide the firefighters and the survivors to safety. Furthermore, it is possible that the sensor readings on-board the UAVs are imperfect (e.g., due to either sensor quality or UAV motion) or the measured data cannot be delivered to a central station for processing due to limited communication ranges. Such likely conditions might make centralized coordination unfeasible. Our theoretical analysis of coordination algorithms, under limited communication and imperfect sensing constraints, show that for cooperative search, it is more beneficial to conduct both information merging and decision-making in a distributed way. Furthermore, UAV networks are highly mobile in 3D, but the UAV movements can be coordinated to adapt to communication needs. Communication-aware coordination algorithms need to be developed for efficient information-dissemination and area coverage.

- In our case studies, we used WLAN in infrastructure mode; i.e., the sensed data from each UAV is delivered to the ground control, processed there, and feedback can be given to the UAVs with new tasks if necessary. This approach is efficient, since the ground control has more computational power than the UAVs. However, it is limited by the transmission range of the ground control and the UAVs. Either the planned paths need to guarantee that the UAVs do not leave the communication coverage of the ground control or the communication&networking block needs to allow operation in ad hoc mode and maintain multi-hop routes between the UAVs and the ground control [20]. Since the wireless channel fluctuates due to motion and multi-path fading, even if the UAVs are always within the average transmission range, all-time connectivity cannot be guaranteed and this issue has to be dealt with.

- We have also tested the performance of our UAV network in ad hoc mode. We used the standard IEEE 802.11s mesh network implementation to determine its performance and limitations. This implementation uses Hybrid Wireless Mesh Protocol (HWMP) (a variant of ad hoc on demand distance vector routing (AODV)) by default for routing. Our experiments resulted in high variance in throughput when the UAVs are mesh nodes in comparison to the infrastructure mode. This is not suitable for applications that demand high throughput with low jitter. Furthermore, depending on the application, real-time protocols (e.g., for SAR) or delay-tolerant networking (e.g., for large area coverage such as oceans) might be more suitable. The protocols might need to handle frequent disruptions and partitioning for applications that require large area coverage with few, limited-range UAVs. Networking protocols, hence, need to be more mission and/or application aware.

- Our in-depth analysis of quantitative and qualitative communication demands of UAV applications in [6] shows that it might not be possible to design a global aerial network that can be deployed for or adapt to the needs of any application. Experimental results (own and other) show that IEEE 802.11 WLAN can provide high throughput and meet the requirements of many applications even though it is not optimized for such highly mobile networks. However, a reliable wireless technology that can sustain high throughput over long ranges is still lacking. A detailed analysis of the suitability of existing wireless technologies including LTE, WiMAX, and Zigbee can be found in [6].

- An alternative or complementary approach to deal with network congestion or other temporary communication constraints is to adapt the payload data (e.g., pictures or video) in terms of quality and, hence, data rate requirements to the network conditions at hand. A further option is to use scalable visual data encoding and transmission to deliver coarse-resolution data first and resolution-refining data subsequently, if and when network conditions permit. We tested both options, the former one dynamically configuring a drone's camera settings depending on a crucial parameter indicating the current drone-to-ground station link throughput conditions [24], the latter one using JPEG2000 pictures for incremental image mosaicking [15]. While these approaches and the prototype systems served us well in our case studies, such communication and adaptation facility is closely tied to, and has to be designed and implemented targeted to, the specific application requirements and networking situation at hand.

6. Related work

Several projects on multi-UAV systems were mentioned in Section 2. In the following, we provide work related to the individual building blocks of multi-UAV systems.

6.1. Sensing

Visual inspection and surveillance is an inseparable part of any multi-UAV system. Aerial images have been used for various purposes including disaster management, site inspection, object/human detection or tracking, etc. [23, 14]. Analyzing the sensed data from an individual UAV fits more in the direction of image processing and many researchers have focused on this direction for various types of sensors. On the other hand, analyzing the data arriving from multiple mobile sensors arises different challenges and increases the complexity of the data analysis. Working with sensor networks we need also to cope with data acquisition, data mining, sensor fusion, time synchronization, etc. Unfortunately, not many researches have been done in real cooperated sensing with multi-UAV systems as much as the individual sensing is performed. Some have combined thermal and visual aerial sensors with multiple UAVS and achieved hyper-spectral images with sensor fusion and inter-spectral image registration [17]. Other works have exploited the stereo vision from multiple UAVs without GPS for ground mapping and path planning [25]. In addition to offline image mosaicking, some methods for real-time image mosaicking and video surveillance, on the fly, have been proposed [26]. However, to achieve higher levels of collaboration and autonomy using heterogeneous multi-UAVs and different types of sensors, a well-defined architecture for reasoning and perception is necessary [27].

6.2. Communication and networking

Site monitoring with UAVs is similar to coverage problem with sensor nodes, which has been investigated by several researchers. In static wireless sensor networks, in general, the coverage problem is treated as a node-activation and scheduling problem (see [28],[29],[30]). More specifically, algorithms are proposed to determine which sensor nodes should be active such that an optimization criterion is satisfied. The criterion can be, for instance, minimizing the coverage time, achieving a certain event detection probability, or covering each point in the area by at least k sensors. In addition, there are also studies that take into account not only the event (or network) coverage, but the connectivity of the wireless sensor network as well [28]. While deciding which sensor nodes should be active at a given point in time, coverage and connectivity requirements are met. Mobile sensor networks have been under investigation and it has been shown that mobility, while complicating the design of higher layer algorithms, also can improve the network, for instance, in terms of capacity, coverage, etc. [31],[32]. Optimum mobility patterns for certain applications are proposed, such as mobile target tracking, chemical detection, etc. using both ground and aerial vehicles. Mobile robots with swarming capability that operate cooperatively and aim to achieve a global goal have also been considered (see [33],[34],[35],[2],[3]).

There is a myriad of literature on routing and medium access protocols for mobile ad hoc and sensor networks. Routing protocols take into account several quality of service metrics as well as energy limitations especially for wireless sensor networks. There are flat [36, 37, 38], hierarchical [39, 40], and location-based protocols [41, 42, 43, 44], where nodes operate in a uniform manner, the network is divided into clusters, or the position of the nodes are incorporated into the routing process, respectively. A comprehensive analysis of the applicability of these routing protocols to UAV networks can be found in [45]. In addition, several extensions to wireless sensor networks are proposed where a mobile node, e.g., a single UAV, is used as a relay or as a mobile base station that collects data from the sensors, or multiple UAVs are used to create a communication chain between otherwise disconnected regions, where no infrastructure exists, e.g., due to a disaster [3, 46, 47]. There are few related works about MAC protocols for wireless sensor networks where UAVs are used as communication relays and range extension [48, 49]. More MAC protocols are proposed for sensor networks supporting mobility (not necessarily with UAVs) [50, 51, 52, 53]. Both contention- and schedule-based methods are investigated. Mobility in sensor networks in general makes scheduling transmissions infeasible and several of the proposed works aim to deal with the drawbacks of mobility. Since the UAVs can control their mobile paths, mobility can be exploited to deliver and collect data in a more efficient way in multi-UAV systems.

6.3. Coordination

The coordination of the actions the individual UAVs execute is required in every multi-UAV system to complete the mission in the best possible way. In this context, the multi-UAV system must steadily decide on where UAVs should move and what tasks they should execute in order to adapt to changes in the environment and to deal with uncertain information. Thus, coordination algorithms can be classified among serveral dimenions including (i) the actions they need to decide on, (ii) the information they use for the decision making, (iii) the decision making algorithms and (iv) and the degree of decentralization [54, 55].

In a multi-UAV system, the coordinated actions range from low-level motions, for example to establish and maintain flight formations, over waypoint navigation to planning complex mission such as cooperative tracking (CT), cooperative search, acquisition and track (CSAT) or cooperative multi-robot observation of multiple moving targets (CMOMMT) (e.g., [56, 57, 58, 59]). While some coordination algorithms use prior information and have exact or partial decomposition of the areas, some use sensor-based information in unknown environments to make coordination decisions. A tradeoff exploration between the information exchange and decision making can be found in [22]. Many decentralized coordination algorithms adopt the concept of multi-agent systems [60] where autonomous and self-interested computational components (agents) are able to control their own behavior. For decision making among autonomous agents a variety of methods are applied such as voting, consensus or game theory algorithms.

7. Open issues

We have presented several issues to be addressed based on our own evaluations via simulations and real-world experiments in Section 5.4. In the following, we elaborate on further issues regarding system integration and interaction between the discussed building blocks of the multi-UAV system. We also summarize some issues related to specific building blocks. As mentioned, the design of multi-UAV systems is application-dependent. In this section, we mainly focus on open issues that are part of our current and future research, regarding area coverage and SAR with UAVs, especially from the sensing and coordination viewpoints.

7.1. *Interdependence between design blocks*

7.1.1. *The UAV platform and sensing block*

The flight dynamics of quadcopter platforms (e.g., tilting, sensitivity to wind and weather) as well as the position and orientation of the UAVs have a great impact on the communication links. In addition, processing of the data requires a high computational power, which might not be feasible on UAVs. The routes the UAVs need to fly (regardless of being designed before or during the mission) on the other hand are affected by sensed data quality. The sensors on-board the UAVs can be imperfect or the sensor data analysis might not be able to return a conclusive finding. In such cases, a feedback from sensing needs to be given to the coordination module, either to repeat the tasks or to adapt the ongoing plan accordingly.

7.1.2. *The communication&networking and coordination blocks*

Communications have a direct impact on the coordination of the vehicles, and hence, on the success of the mission. The sensed data need to be delivered to the ground control and new tasks or mission requirements need to be delivered to the UAVs. WLAN 802.11 is limited and can be a bottleneck, especially if large data amounts need to be transferred (e.g., in case of high quality images and real-time video streaming). Large data amounts also have impact on the mission times. Similarly, if the vehicles are coordinated such that the data needs to be collected simultaneously by many vehicles with different points of view, data exchange and processing can become a challenge. Especially, if the on-board sensor is a camera, registering and mosaicking images from different UAVs, possibly different cameras, with different view angles and altitudes (and hence different resolution) is a great challenge.

7.2. *Multi-UAV system design blocks*

The readers are referred to the recent surveys [61, 12, 6, 45] for detailed open issues on networking protocols (i.e., routing and MAC), required wireless technology, spectrum allocation, antennae, communication security for safe operation, and application-dependent communication for UAV networks. In addition to the issues discussed in these surveys, reliable coordination and data delivery among the UAVs and the ground station is required for safe autonomous operation. It is not yet clear whether an existing wireless technology can support such reliability in a highly mobile network with 3D motion capabilities.

It is also largely open, at least in the general case, how an application can get concise, yet reliable information about the current network status such as to potentially adapt its data communication and QoS requirements or to cope with reduced sensed-data quality at times. This is a typical cross-layer networking issue. While we used the packet queuing delays on the outgoing link as a good indicator of current network throughput in one of our use cases [24], other communication&networking situations might require other parameters to be monitored. Acquiring and disseminating more experience here would help advance the field.

In coordinated multi-UAV search and rescue, we generate paths for all UAVs optimized for time at the beginning of the mission and adapt if a target is found. For missions with more dynamic goals, e.g., for mobile targets, or for large UAV networks, a more suitable approach might be coordinated by on-line decision making, where each UAV decides its movement for the next few time steps. Novel multi-UAV applications will increase the complexity, dynamics and uncertainty the coordination methods have to deal with which makes *optimal* coordination very difficult to achieve. A particular challenge for coordination is therefore to deal with *system-level properties* such as robustness, safety and mission reachability. Furthermore, while UAV-vision is used as a tool for collision avoidance or automatic landing for larger aerial vehicles, a robust vision based coordination (i.e., navigation and control) is missing for use in small-scale UAVs.

7.3. Efficient evaluation methods

It is difficult to evaluate the interdependence of the design blocks as well as the overall performance of the multi-UAV systems. Simulators are useful to a certain extent, however, real-life dynamics of the system cannot be fully grasped using simulation only, thus experimental testbeds are required. Several testbeds exist to evaluate multi-UAV control algorithms. However, there is still a lack of testbeds to evaluate the sensing, communication&networking, and coordination algorithms for the multi-UAV systems. At a minimum, the impact of flight dynamics on communication links, sensed data quality, and the impact of small-scale vehicle characteristics such as short flight times and low payload on coordination can be better modeled via input from real-world tests.

7.4. Autonomy and user interaction

Finally, most applications require some autonomy in the flight operation of the UAVs. While this may be *preferable* for single-UAV applications, autonomous flight operation is *required* for multi-UAV systems. Autonomy helps to simplify and abstract the user interface. With autonomy and an efficient user interface design, the users can focus on the overall mission and do not need to deal with individual UAVs (as we have demonstrated with our map-based user interface). Methods to achieve high levels of autonomy and low levels of user interaction are required.

7.5. *Integration of UAVs into existing systems*

The focus of this paper has been on multi-UAV systems deployed as ”stand-alone” systems toward achieving certain mission goals (such as fast area coverage, relay network formation), where the UAVs could be sensor and/or relay nodes. However, it is envisioned that multi-UAV systems will likely be a part of an existing infrastructure (e.g., part of a large rescue operation in a disaster, data mules for a large wireless sensor network, mobile base stations in future communication networks, a part of a large delivery network, etc.). Therefore, even if the UAVs have their own goals to meet, they need to consider the challenges associated with the *larger systems* for efficient integration and operation, such as scalability, increased data volume, varying communication interfaces, co-existing with other networks, and information processing from a heterogeneous set of devices. Having limited payload, computation power, data storage, it is yet not clear how the UAVs should be integrated into the emerging large-scale networks.

8. Conclusions

We introduced a high-level architecture for the design of drone networks that consist of UAVs and ground stations with sensing, coordination, and communication&networking functionality. We demonstrated, in different scenarios, the capabilities of a network of quadcopters designed following the principles of the proposed architecture. From several real-world tests, we observed that for effective design of drone networks, especially for dynamic applications, focus should be given to better defining the interactions between sensing, coordination, and communication, as well as the constraints imposed by the application at hand. Our current research focus is on advanced modeling and designing a multi-UAV system. While there are still many open issues for achieving an ideal multi-UAV system, we are confident that the applications UAVs are deployed for will keep on increasing and multiple-UAVs will occupy our skies in the near future.

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Vitae

Evşen Yanmaz received the B.S. degree in electrical and electronics engineering from Bogazici University in 2000; the M.S. degree in electrical engineering from SUNY at Buffalo in 2002; and the Ph. D. degree in electrical and computer engineering at Carnegie Mellon University in 2005. She is a senior researcher and Project Leader at Lakeside Labs, Klagenfurt, Austria. Previously, she held positions as Senior Researcher at NES Institute at Alpen-Adria-Universität Klagenfurt, as postdoctoral researcher at the Los Alamos National

Laboratory, as researcher at Carnegie Mellon University, and as an intern at Nokia Research Center, USA. Her research interests include self-organizing networks, cooperative networks, and coordination of airborne and ground sensor networks.

Saeed Yahyanejad received the B.Sc. in Applied Mathematics and the M.Sc. in Information and Communication Systems Security. He has joined the Pervasive Computing Group, Alpen-Adria-Universität Klagenfurt, Austria in September 2009. There he received his PhD working on multispectral mosaicking of images taken by small scale UAVs. Currently he is a senior researcher working in the fields of cognitive robotics, sensor networks, and machine perception at Joanneum Research-Robotics, Austria.

Bernhard Rinner received the M.Sc. and Ph.D. degrees in telematics from the Graz University of Technology, Graz, Austria, in 1993 and 1996, respectively. He is a Full Professor and the Chair of Pervasive Computing with Alpen-Adria-Universität Klagenfurt, Klagenfurt, Austria. He held research positions with the Graz University of Technology from 1993 to 2007 and with the University of Texas at Austin, Austin, TX, USA, from 1998 to 1999. His current research interests include embedded computer vision, aerial robotics, sensor networks, and pervasive computing. Dr. Rinner is an Associate Editor of the Ad Hoc Networks Journal and EURASIP Journal on Embedded Systems. He is a member of the board of the Austrian Science Fund (FWF).

Hermann Hellwagner is a full professor at the Institute of Information Technology, Alpen-Adria-Universität Klagenfurt, Austria, leading the Multimedia Communications group. His current research areas are distributed multimedia systems, multimedia communications, and information-centric networking. He has published about 200 scientific papers on parallel computer architecture, parallel programming, and multimedia communications and adaptation. He is a senior member of the IEEE, member of the ACM, and was Vice President of the Austrian Science Fund (FWF).

Christian Bettstetter received the Dipl.-Ing. degree in 1998 and the Dr.-Ing. degree (summa cum laude) in 2004, both in electrical and information engineering from Technische Universität München (TUM), Munich, Germany. He was a research and teaching staff member at the Institute of Communication Networks, TUM, until 2003. From 2003 to 2005, he was a senior researcher with DOCOMO Euro-Labs. He has been professor at the University of Klagenfurt, Austria, since 2005, and founding director of the Institute of Networked and Embedded Systems since 2007. He is also the founding scientific director of Lakeside Labs, a research company on self-organizing networked systems. His research interests are in wireless communications and self-organization in networked systems with applications to telecommunications and robotics. He received paper awards from the IEEE Vehicular Technology Society and the German ITG. His papers have been cited more than 10,000 times. He is a senior member of the IEEE and member of ACM SIGMOBILE.