Communication and Coordination for Drone Networks

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Abstract. Small drones are being utilized in monitoring, delivery of goods, public safety, and disaster management among other civil applications. Due to their sizes, capabilities, payload limitations, and limited flight time, it is not far-fetched to expect multiple networked and coordinated drones incorporated into the air traffic. In this paper, we describe a high-level architecture for the design of a collaborative aerial system that consists of drones with on-board sensors and embedded processing, sensing, coordination, and communication&networking capabilities. We present a multi-drone system consisting of quadrotors and demonstrate its potential in a disaster assistance scenario. Furthermore, we illustrate the challenges in the design of drone networks and present potential solutions based on the lessons we have learned so far.

Key words: drones, unmanned aerial vehicle networks, wireless sensor networks, vehicular communications, cooperative aerial imaging

1 Introduction

Autonomous unmanned aerial vehicles (UAVs), also called drones, are considered with increasing interest in commercial applications, such as environmental and natural disaster monitoring, border surveillance, emergency assistance, search and rescue missions, and relay communications [1–6]. Small quadrotors are of particular interest in practice due to their ease of deployment and low acquisition and maintenance costs.

Research and development of small UAVs has 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 networked aerial vehicles. 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. 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 for different applications (see [6] and references therein). For civil applications, the design principles of a multi-UAV system, however, still need investigation and remain an open issue. In this paper, we summarize challenges for the design of a system of multiple small UAVs, which 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. The hardware and low-level control, on-board sensors, and interpretation of sensed data are out of the scope of this paper.

Our main goal is to provide an overview of the design blocks and 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 a case study in a real world disaster scenario, where we show how we can support firefighters with our aerial monitoring system. We envision that the lessons learned in our experiments will guide us toward achieving an effective multi-UAV system.

2 Multi-UAV System Overview

Important properties of a multi-UAV system to realize its full potential are its robustness, adaptivity, resource-efficiency, scalability, cooperativeness, heterogeneity, and self-configurability. To achieve these properties, the physical control of individual UAVs, 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 wireless ad hoc and sensor networks, robotics, and swarm intelligence research communities provide valuable insights into one or more of these functionalities as well as combinations of them [7–9].

The past decade observed several projects with UAVs for civil applications (e.g., UAV-NET, COMETS, MDRONES, cDrones, OPARUS, AUGNet, RAVEN testbed, sFly, and MSUAV [6]). A classification can be made for these works, first, on the type of vehicles used, such as helicopters, blimps, 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 have recently been explored [6]. While these projects start from different assumptions, focus on different functionalities, and aim to address different constraints, in principle they satisfy some common design paradigms. Accordingly, one can come up with an intuitive conceptual diagram that captures the essence of multi-UAV systems, which consists of multiple vehicles (*UAVs*) that observe the environment (*sensing*) and implicitly or explicitly communicate the observations to other vehicles (*communication&networking*)

to achieve a common goal via planning their paths and sharing tasks (*coordination*). Depending on the application at hand, existing multi-UAV systems focus on the design of one or more of these blocks. For instance, MDRONES focuses on the design of autonomous small-scale UAVs; COMETS consists of sensing, coordination, and communication subsystems [9], and sFly focuses on a combination of UAVs, sensing, and coordination blocks.

The optimal method of integrating these blocks, designing the necessary interaction and feedback mechanisms between them, and engineering an *ideal team* of multiple UAVs are important issues to be addressed.

3 General Collaborative Aerial System Architecture

There are several challenges in developing a system of collaborative UAVs. Especially, the interaction between the hardware, sensing, communication&networking, and coordination blocks of the high-level architecture is still an open issue. In the following, we summarize the desired functionalities in these blocks as well as the associated challenges with an emphasis on communication&networking and coordination.

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. Whether 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* their environment,
- evaluate their own observations as well as the information received from other UAVs, and *reason* from them, and
- *act* in the most effective way.

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

The *communication&networking* block is responsible for information dissemination. This block needs to be robust against the 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 needs 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 within this block are:

- *Maintaining connectivity*: In a disaster, it is likely that a communication infrastructure is lacking. Hence, use of UAVs as relays between disconnected ground stations might become imperative. The 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 highly 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*: Small-scale quadrotors have specific layouts and constraints different from fixed-wing UAVs. Link models that capture the characteristics of such UAV-UAV and UAV-ground links are needed.

The *coordination* block is responsible for using local observations and observations from other UAVs, mission requirements, and system constraints to organize the UAVs. In a nutshell, it needs to compute the trajectories of the vehicles and make decisions on how to allocate tasks to achieve team behavior. The 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 protocols are necessary 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 proposed for ground robots and also 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.

While not in the scope of this paper, advances in UAVs and sensing blocks are also essential. Especially, techniques for efficient data fusion from multiple heterogeneous sensors, interpretation of the data and feedback mechanisms to the coordination block, as well as effective obstacle and collision avoidance methods need to be developed for the small-scale vehicle networks.

This general overview can provide some guidelines in the design of multi-UAV systems with different capabilities and with different constraints imposed by different applications. We have been working on a representative system (http://uav.aau.at/), details of which we present in the following.

4 Collaborative Drones Network

Our collaborative drone system has focused on sensing, communication, and coordination blocks of the general architecture using commercial quadrotors. Sensing capabilities and desired sensor coverage as well as resource limitations of the UAVs (e.g., flight time) are available to the coordination block [10]. The amount of sensor data to be delivered is utilized in the communication&networking block during scheduling of transmissions [11]. 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 [10, 12].

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 capture aerial images and provide an overview image of the monitored area in *real time*. Figure 1 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. The UAVs then fly over the area of interest and acquire images. The images are sent to the ground station and mosaicked to a large overview image. 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; (iii) a communication infrastructure; and (iv) the UAVs with their on-board processing and sensing capabilities.

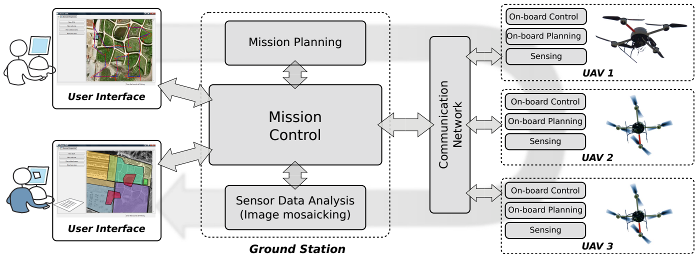
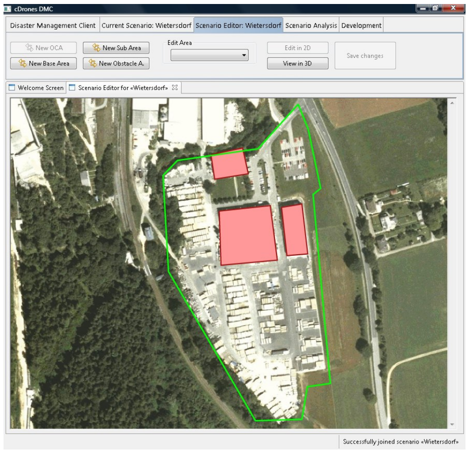


Fig. 1. System architecture: Double-headed arrows indicate interactions between individual modules while the shaded arrow in the background indicates the basic operation flow.

The *User Interface* has two main purposes. First, it allows the user to define the high-level tasks to be accomplished by roughly 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 2). Second, it provides the user with the generated mosaicked image with the current position of the UAVs. During mission execution, the user can change the tasks as needed. The *Ground Station* 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). We have developed both centralized and decentralized mission planning strategies to handle static and dynamic environments [10, 12]. 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 [13]. Our system does not impose special requirements on the communication infrastructure. 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 [14–16].

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 preprocessing the image data on-board before transmission to the ground station. Preprocessing includes feature extraction, annotation with meta-data, quality checks (to delete blurred images), and multi-resolution encoding.



Successfully joined scenario «Wietersdorf»

Fig. 2. User interface showing the observation area (green polygon) and forbidden areas (red polygons) defined by the user on a digital map.

We support heterogeneous UAVs that provide 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 UAV's on-board control translates these generic commands into the UAV-specific low-level commands. In our system, we use quadrotors from Microdrones and Ascending Technologies (Fig. 3). We consider both centralized and decentralized approaches for coordination (planning and sensor analysis) and communication modules. In the decentralized case, planning functionality is migrated from the ground station to the UAVs.

5 Disaster Management Case Study and Lessons Learned

We demonstrated our system in several real-world applications, including assistance during a disaster and documenting the progress of a large construction site. We took

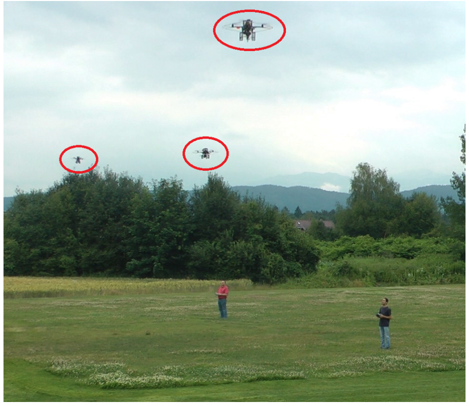


Fig. 3. Three AscTec Pelican drones taking off for a mission at the University of Klagenfurt campus.

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 2 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 4 depicts the computed plan using an integer linear programming strategy [10] 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 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 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

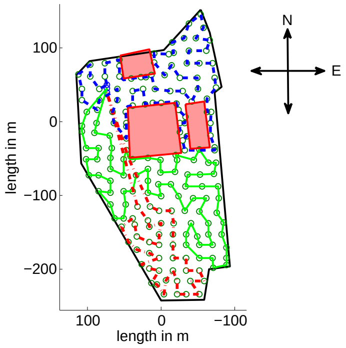


Fig. 4. Mission plan for three UAVs to cover the area of interest

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 [11]. 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 5 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.

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	A2G, G2A,	single-hop	UDP: 14 Mbps (350 m), 29 Mbps (50 m) [14]
($P_{tx} = 20$dBm)	A2A	single-hop	TCP: 10 Mbps (500 m), 17 Mbps (100 m) [15]
802.11n ($P_{tx} = 12$dBm)	A2G, G2A,	single-hop	TCP: 10 Mbps (500 m), 100 Mbps (100 m) [16]
802.11ac($P_{tx} = 10$dBm)	A2G, G2A,	single-hop	TCP: 5 Mbps (300 m), 220 Mbps (50 m) [16]
802.11a + 802.11s ($P_{tx} =$ 12dBm) [15]	A2G	multi-hop	1-hop: 5 Mbps (300 m)
(fixed PHY rate: 36 Mbps)	A2A–A2G	multi-hop	2-hop: 8 Mbps (300 m, infrastructure mode) 2-hop: 5 Mbps (300 m, mesh mode)

Lessons Learned

In the following, we elaborate on the performance of the overall system and the individual functional blocks.

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

- The *Mission Planning* component generates a deterministic 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). The time needed to cover the whole area could be reduced depending on the desired image quality. This can be done by choosing less overlap between neighboring pictures and/or using a higher flight altitude.
- *Sensor Data Acquisition and Analysis*. 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 the optimization goal is a visually appealing panorama from single viewpoint. In our mosaicking approach, spatial accuracy is more desirable than the visual appearance.
- 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, the trajectories cannot be determined beforehand. A distributed and adaptive coordination can also give further capabilities and response options in a disaster management scenario such as the fire drill. The UAVs can be used to track the boundary of the hazardous materials or guide the firefighters and the survivors to safety.
- In our case study, 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 [15]. Since the wireless channel fluctuates due to motion and multi-path fad-

ing, 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.

Fig. 5. Part of the overview image stitched from approx. 40 pictures taken during the firefighter's practice along with the UAV's trajectory (red path).

6 Conclusion and Open Issues

We illustrated a high-level architecture for the design of multi-UAV systems that consist of vehicles with on-board sensors and embedded processing, and sensing, coordination, and communication&networking blocks. We presented a system consisting of quadrotors and demonstrate its potential in a disaster scenario.

From several real-world tests, we have observed that for effective design of multi-UAV networks, especially for dynamic applications, special focus should be given to better defining the interactions between the design blocks in addition to addressing the issues we summarized specific to communication&networking and coordination blocks. Our current research focus is on addressing those issues and on advanced modeling and designing a multi-UAV system. Our evaluations via simulations as well as real-world experiments so far give us the following insights into the capabilities and requirements of multi-UAV systems:

1. Strong interdependence between design blocks
   - Impact of the UAV platform and sensing block
     The flight dynamics of quadrotor platforms (e.g., tilting, sensitivity to wind and weather) as well as 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 coordination module, either to repeat the tasks or adapt the ongoing plan accordingly.
  - Impact of 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.

2. 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 with only simulators, 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.
3. 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.

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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