Multidrone Systems: More Than the Sum of the Parts

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Now that drones have evolved from bulky platforms to agile devices, a challenge is to combine multiple drones into an integrated autonomous system, offering functionality that individual drones cannot achieve. Such multidrone systems require connectivity, communication, and coordination. We discuss these building blocks along with case studies and lessons learned.

Small and human-friendly drones enable novel applications in many domains.[1,2] They assist rescue personnel with real-time aerial videos and transport urgent goods in case of disasters or lockdowns. They play a prominent role in precision agriculture and inspection of infrastructure.

First-generation drones were remote-controlled unmanned aerial vehicles (UAVs) with limited sensing and navigation capabilities. Today's 2G systems feature automated waypoint flights, high-resolution sensors, and wireless connectivity. Third-generation drones will offer a higher level of autonomy in terms of navigation and decision making. Systems in which single drones operate in isolation evolve toward systems in which multiple drones operate collectively as an integrated networked system. Of course, multiple drones perform certain missions faster or better than a single drone. But beyond this, drones can coordinate and collaborate for new functionality that is more than the sum of its parts.

Digital Object Identifier 10.1109/MC.2021.3058441
Date of current version: 7 May 2021

In aerial inspection, for example, we need several coordinated drones in the air to perceive an area simultaneously from different viewpoints and then exchange and fuse the data.

Such multidrone systems (MDSs) have been the subject of our research at the University of Klagenfurt, Austria, for more than 10 years (go to uav.aau.at). This article addresses the three key building blocks required to transform multiple single drones into an MDS: connectivity, communication, and coordination. *Connectivity* provides the hardware and software for wireless interconnection among the drones and to the ground; *communication* handles data distribution on top of connectivity; and *coordination* manages the tasks that need to be executed. We discuss the functionalities and design challenges of these blocks, considering the limited onboard resources; report about three case studies with different implementations of the building blocks; and conclude with a discussion of lessons learned.

FROM SINGLE SYSTEM TO MDS

The basic data processing on board a typical drone follows a sense-process-act cycle executed at multiple levels. Low-level flight control samples and fuses the data from sensors—such as an inertial measurement unit, a global navigation satellite system (GNSS), a barometer, and cameras—and executes control algorithms to set the actuators for the rotors at rates of 100–1,000 Hz. It stabilizes the drone in position and attitude and provides basic control modes, such as manual and waypoint flights. Advanced flight control can be assigned to mid-level processing. It exploits additional sensors—such as more cameras and range sensors—to monitor the nearby surroundings and react to obstacles. Additional data fusion and object detection are required, typically processed at a rate of 2–30 Hz. Data from cameras and related sensors are used to generate map-like representations of the environment, which serve as input to long-term reasoning on how to complete the overall mission. Long-term reasoning is essential for increased autonomy and includes learning, planning, and optimization. The timing requirements for high-level reasoning are more relaxed than those for low-level control.

Figure 1 depicts the architecture of an MDS with the extended sense-process-act cycle in each drone. The blue arcs indicate the dataflow from the sensors to the actuators, and the blocks represent the key functional units. The central block subsumes the onboard high-level processing, including the encoded knowledge and the available reasoning. This knowledge includes information about the drone (for instance, sensing and motion capabilities, position, and attitude), its environment (such as map data and positions of other drones and objects), and the mission (for example, routes and target positions). The knowledge is provided before the mission begins and is continuously updated during the mission. The orange components in Figure 1 depict the fundamental components for converting the individual drones into an MDS. Communication distributes data among the drones and relies on the connectivity components. Coordination is responsible for sharing knowledge among the drones and adapting the reasoning techniques such that drones jointly act toward completing the mission.

An MDS is a distributed, embedded system with tight, real-time requirements and dynamically changing constraints on processing, sensing, and energy. Thus, all functions must be well aligned

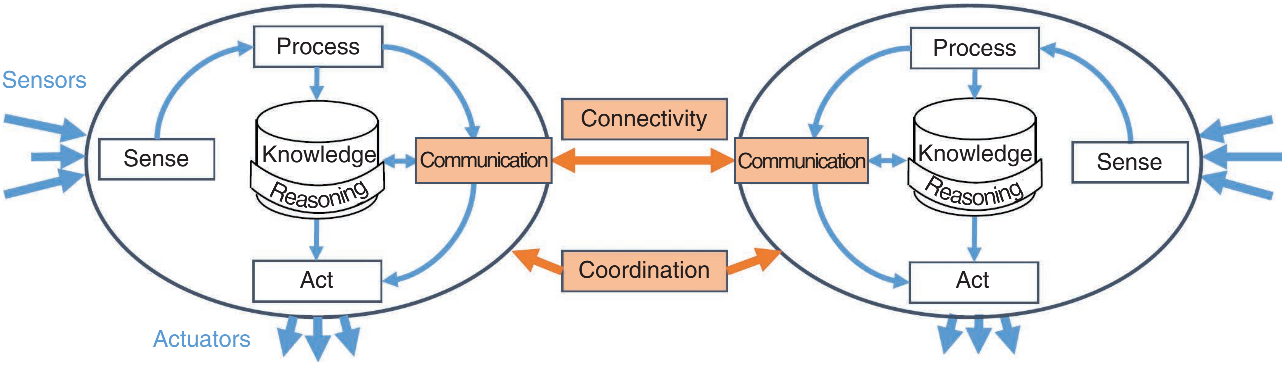

FIGURE 1. The architecture of an MDS: the fundamental data processing of individual drones is expanded by the essential functionalities of connectivity, communication, and coordination.

with the available resources and mission requirements. In some settings, the available resources on board are insufficient, making it necessary to offload the computation along with the relevant data to a ground station or other infrastructure at the edge of the network. Figure 2 shows the distributed processing in an MDS, where computation can take place either on or off board.

The offloading of computations must consider the additional latency. The decision for a transfer is based on the turnaround time of the offboard computation T, which can be estimated as

$$T = \frac{P}{S} + 2\tau + \frac{D}{R}, \quad (1)$$

where P represents the onboard processing time, S the speedup of edge over drone computation, τ the communication delay, D the amount of transferred data to and from the offboard unit, and R the data transfer rate.

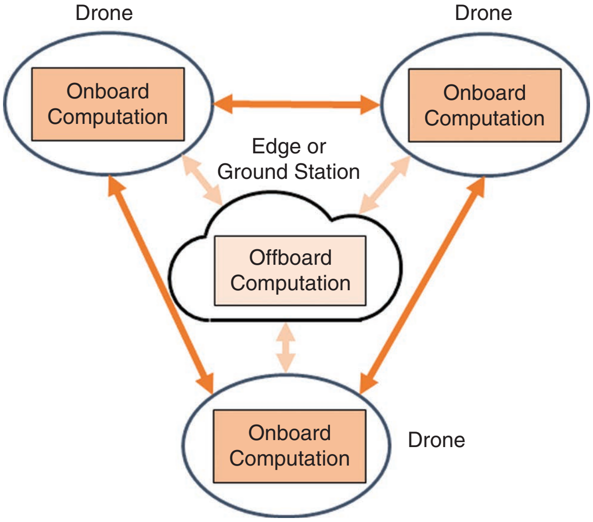

FIGURE 2. Computation in an MDS takes place locally (onboard processing of local data) and in collaboration with other drones (onboard processing of data received from others). Because of resource constraints, computations may be offloaded to an edge computing infrastructure or a ground station.

COORDINATION

Coordination is concerned with sharing knowledge, joint decision making, and allocation of computation tasks to processing nodes. Different levels of coordination exist—ranging from high-level functions, like the assignment of system-wide tasks and resources, down to low-level control, like collision avoidance, flight formations, and joint sensor usage for state estimation. The way coordination is resolved in a particular MDS strongly depends on the mission type and the importance of different constraints. In fact, the design space is huge: different constraints have to be taken into account, such as energy, connectivity, deadlines, and physical payload. Furthermore, varying means of realization (offline versus online, centralized versus decentralized, fixed versus adaptive, and explicit versus implicit data exchange) and optimization methods are used.[3]

Offline coordination occurs before the mission begins, often casts the mission as an optimization problem with various constraints, and exploits advanced optimization or approximation techniques to find (near-)optimal solutions.[4] The computational effort for offline coordination is less critical, but it can leverage information about the mission only before it starts. For example, unexpected changes caused by the system dynamics or failures must be compensated for by online techniques during the mission.

The computational effort becomes more important for online coordination. In centralized online coordination, a single entity is responsible for the coordination and therefore requires complete information about the mission's evolution. In distributed online coordination, processing occurs at multiple entities, each with partial information about the mission. Self-organization represents a special case of distributed online coordination, where a coherent group behavior emerges from multiple drones executing simple rules.

WIRELESS CONNECTIVITY

MDSs need robust, high-rate, and low-latency connectivity to transfer commands, images and videos, and other data. Various communication techniques, protocols, and systems have been studied in this context.[5,6] Since Wi-Fi does not always meet the requirements of drone applications, there is a demand to integrate drones into current and future cellular networks. A key observation in current systems is that aerial devices are served by the sidelobes of the base station antennas. Therefore, they typically experience lower throughput than ground users and establish line-of-sight radio links to distant base stations normally invisible to ground users. These untypical links cause problems as they lead to interference[7] and frequent handovers.[8] The performance suffers, in both up- and downlink, affecting even normal ground users, especially when many drones are deployed. Experiments made with a drone connected to a commercial 4G network show that the average downlink throughput drops from 65 Mbit/s at the ground to about 20 Mbit/s at a typical flight altitude of 150 m in a certain setup.[9]

These challenges have been taken up by the 3rd Generation Partnership Project standardization, where different working groups want to ensure that 5G networks meet the demands of drone applications. Once wireless connectivity solutions have been deployed, drones can communicate over this infrastructure with a high rate and low latency to exploit it for other purposes, such as computation and data fusion.

COMMUNICATION

A communication component in every drone is responsible for exchanging and distributing sensed data, control, and coordination information to the ground and other aerial devices. Communication must support other components, especially local processing and overall coordination activities, to reach a satisfactory system performance.[10] The data to be communicated are diverse (for example, in terms of size, utility, priority, and sender–receiver patterns) and depend on the specific mission, but they typically involve images, image fragments or descriptors, maps, status information, mission objectives and commands, and traffic involved in joint decision making and coordination. Decisions and communication processes must happen in real time with constraints in terms of computation and energy.

In the multirobot systems community, communication is often framed as optimizing data distribution, that is, deciding *what* data to exchange *when*, *how*, and *with whom* to achieve good overall system performance while minimizing resource utilization. Our work addresses the close interdependence of communication, coordination, and sensing[10] and proposes a utility model to evaluate and optimize communication strategies.[11] Other approaches come from optimization, transport, and game theory, among other fields.[12]

Edge computing offers interesting options for offloading processing tasks from drones. Some of these options are 1) offloading naturally centralized tasks, for example, building an overall map from individual map fragments provided by the MDS devices; 2) offloading heavy computations, such as image feature detection and tracking in a vision-based navigation MDS mission; and 3) offloading the full low-level control cycle of the drones plus their coordination, for instance, when very resource-constrained drones act only as "flying sensors." In all cases and as indicated in (1), the wireless connectivity must guarantee high data rates. More importantly, the requirements on low-latency communication and swift responses from the edge increase for the three examples given, with the latter one representing a true 5G use case of ultrareliable low-latency communication.

MULTIDRONE CASE STUDIES

Our three case studies differ significantly in implementing the MDS functionalities of coordination and connectivity but share similarities in low-level processing and application scenarios.

Area monitoring

Drones equipped with cameras monitor an area of interest to assist rescue personnel in a disaster situation. The drones fly periodically over the area, capture images, and send them to a ground station, where an overview image is generated and analyzed. At the beginning of the mission, the operator specifies the area of interest and parameters such as no-fly zones, target resolution, and priority regions in an electronic map.

The system applies offline coordination with relaxed timing requirements. In particular, area partitioning, allocation of positions for image capturing, and route planning are modeled as a mixed-integer linear programming problem approximated using advanced heuristics at the ground station. The resulting flight plans are uploaded to the drones before the mission begins. During the mission, the drones automatically follow their plans, capture images at the requested quality, and send them to the ground. The operator can follow the updates of the overview image during mission execution.

Connectivity and latency of image delivery are critical for rescue operations. To reduce latency, especially in areas with low connectivity, we progressively encode the images in multiple quality levels on board and perform a prioritized data transfer to the ground. Each image is split into different layers containing different resolution parts scheduled for delivery in five priority queues. Low-resolution parts of newly covered areas have

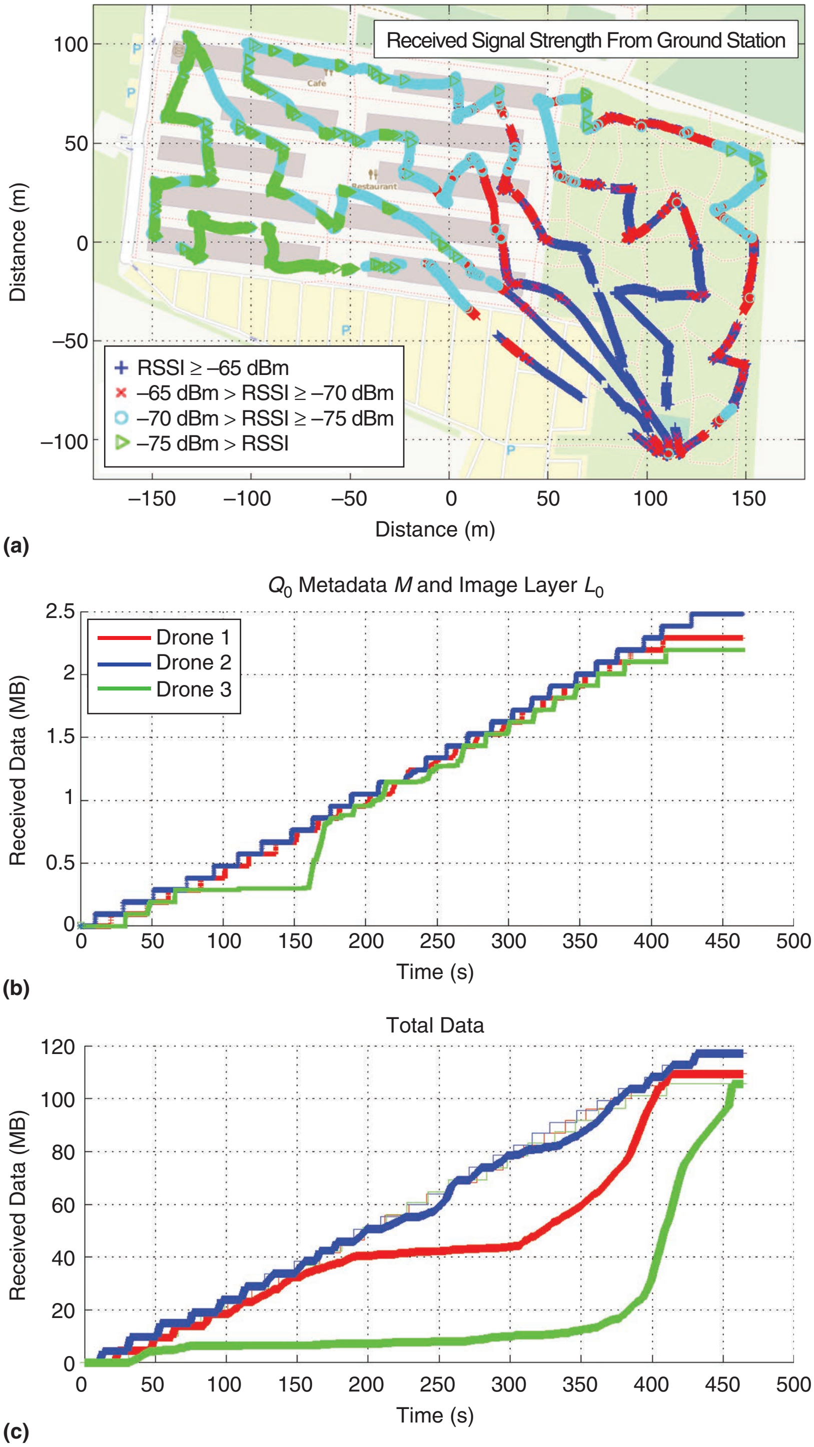

FIGURE 3. Prioritized data delivery for area monitoring. (a) Computed flight routes and received signal strength indicator (RSSI) values, (b) top priority data received over mission time, and (c) complete image data received over mission time. (Adapted from Wischounig-Strucl and Rinner[13], with permission from Springer.)

top priority, and high-resolution parts have lower priorities. Each priority queue is a first-in, first-out queue, and an image layer is transferred only if all higher priority queues are empty. Figure 3 depicts the effect of prioritized data delivery. Even if a drone is monitoring an area with low connectivity [green traces of the drones' routes in Figure 3(a)], the delivery of high-priority data is hardly stalled, and low-resolution images become available at the ground station immediately after image capturing, except for images from drone 3 (UAV_3) during mission period [70, 160] s in Figure 3(b). However, the delivery of full-resolution images from drones 2 and 3 is significantly delayed [Figure 3(c)].

Disaster situations often extend over wide areas that cannot be covered by a single ground station. For this reason, it makes sense to augment coordination with connectivity and plan the flight routes such that connectivity is maintained via relay drones to the ground station.[4] Since this routing problem is NP-hard, we apply cooperative planning heuristics that efficiently find routes with short overall coverage time.

Emergent patterns

There are many phenomena in nature where entities coordinate in a self-organizing way. Important examples are synchronization (coordination in time) and swarming (coordination in space). These two processes were treated largely independently from each other until a mathematical model was proposed that introduced an interaction between them.[14] For example, neighboring entities may synchronize faster, and entities in close synchronicity may attract each other in space. The entities defined in this model, called *swarmalators*, emerge into different types of spatiotemporal patterns.

We adapted and extended the swarmalator model for use in mobile robotics.[15] Besides being visually attractive, the formation of such patterns is also beneficial for stereophotography, artistic drone shows, and other applications. Our doctoral students implemented the model on Crazyflie quadcopters and showcased an aerial swarm in our dronehall (see Figure 4). The main challenge in transferring from theory to practice is to map the time-continuous, delay-free coupling model into a time-discrete, delay-robust protocol for resource-efficient interaction.

Using this approach, drones can form 2D and 3D patterns—like circles or spheres, either static or moving. The patterns emerge without explicit programming of the flight paths and are self-adaptive, which means that drones leaving or joining the formation are handled by the system. The online algorithm can, in principle, run either on board or centrally through a server. It involves the exchange of low-volume data (positions and temporal states) but requires robust connectivity.

Autonomous navigation

Autonomous navigation requires that drones reliably localize themselves, find efficient routes to target positions, and safely move along these routes. Ideally, all this functionality is available in the MDS and works in unknown environments without human intervention. Today's route-planning approaches often use classical sampling-, grid-, or learning-based methods.[16] Navigation relies predominantly on visual and inertial sensor data and is complemented by GNSS data where available. An edge server may support the drones beyond just vision-based navigation tasks and serves as an entity to ensure collision-free movement and create a consistent overall map. Significant computational power on the edge server is required to justify offloading. In addition, low-latency, high-rate connectivity is necessary to transmit the high-volume data to the edge.

We analyzed a standard vision-based navigation algorithm (multistate constraint Kalman filter) and studied three options for offloading low-level localization tasks to an edge

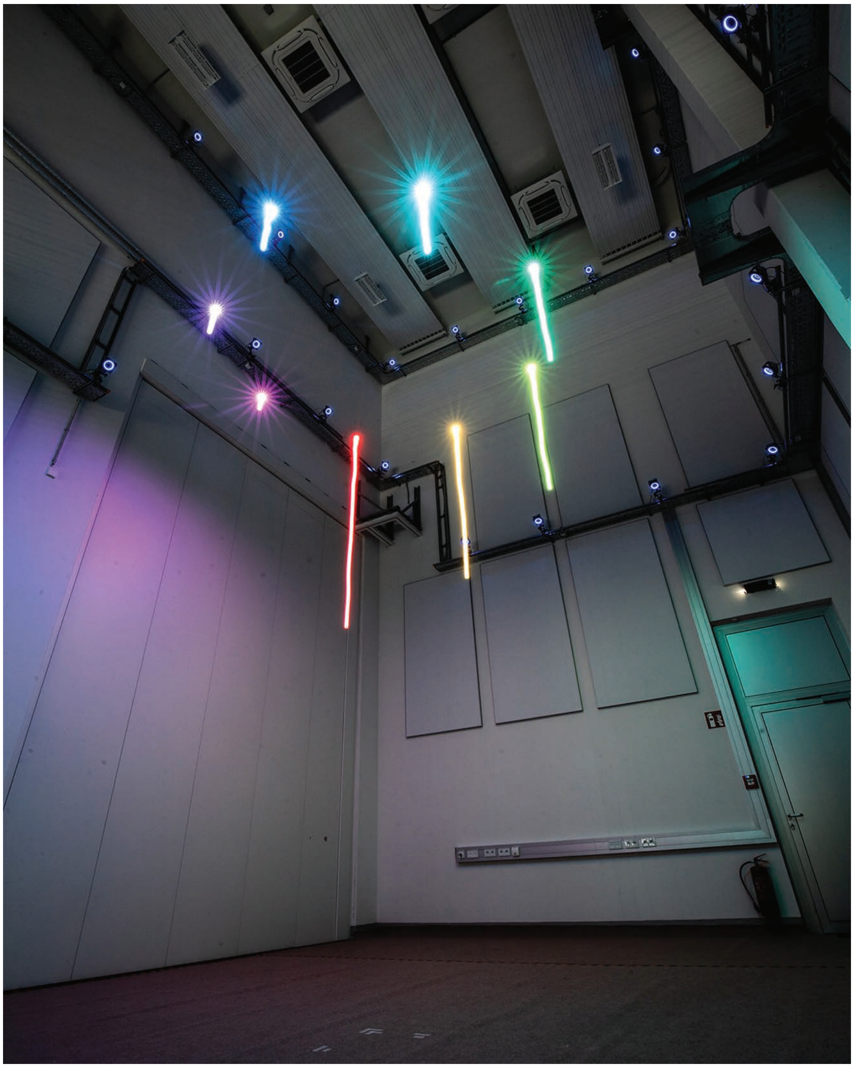

FIGURE 4. Drones fly as swarmalators in the Klagenfurt dronehall. In this example, they emerge into the pattern "static async," a static disk with uniformly distributed, spatially sorted temporal states (colors). (Photo by D. Waschnig for the University of Klagenfurt; used with permission.)

server: complete onboard processing, complete offloading to the edge, and partial offloading.[18] Analyzing (1) helps to assess the three options. The onboard processing capacity of the current small drones is insufficient for accurate and fast vision-based drone navigation. Only low-resolution images can be analyzed, leading to inaccurate state estimation and low state update rates of only a few hertz. Full offloading requires high uplink data rates R, low latencies τ, and significant processing power S at the edge, as envisioned in 5G systems. Only if these conditions apply will full transfer of high-resolution images and processing on the edge improve the accuracy and agility of drone flights. Up to a certain uplink rate, partial offloading is better than full offloading for a given edge computing power. Until full 5G performance with uplink data rates of several hundreds of Mbits/s becomes available, exploring and utilizing partial offloading options will be preferable in our case studies.

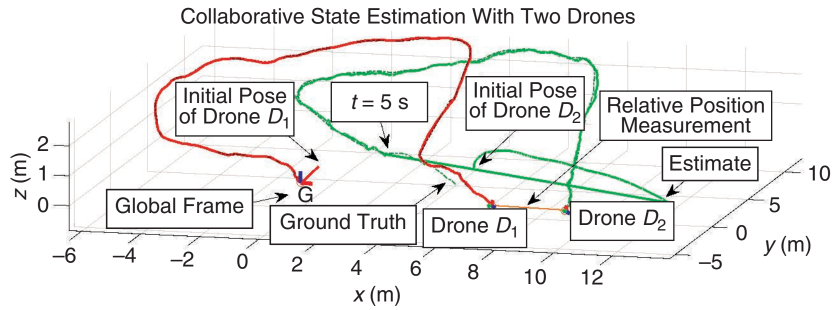

FIGURE 5. Estimated trajectories demonstrating collaborative state estimation of drones D_1 and D_2 in red and green, respectively. D_1 obtains absolute position measurements, whereas D_2 receives only relative position measurements from $t = 5$ s on (explaining the large estimation errors in the beginning before the relative measurements). (Adapted from Jung et al.[17])

TABLE 1. A summary of case studies.

	Area monitoring	**Emergent patterns**	**Autonomous navigation**
Coordination	Centralized offline planning before mission; independent flights without coordination during mission	No flight planning; distributed or centralized online coordination during mission	Hybrid distributed/ centralized (edge) online coordination; offloading decisions
Connectivity	Data transfers to ground only; no interdrone connectivity required	Low-rate connectivity between drones or to ground station	Low-latency, high-rate connectivity including drones and edge
Communication	Decisions as to which image quality layer(s) to transfer and when to do so	Simple periodic exchange of position data and temporal states	Offloading decisions and data transfer; complex data exchange

The distribution of low-level navigation and localization tasks within the MDS represents another alternative for improving resource efficiency. Furthermore, collaboratively analyzing all available sensor data leads to superior performance of the MDS compared to local data analysis of multiple drones. We investigated collaborative state estimation methods,[17] which enable drones to move seamlessly along their routes in areas with heavily distorted or even unavailable sensor signals. The required information, such as the global position, is then propagated through other drones operating in areas well covered by GNSSs (Figure 5). This allows the MDS to explore areas noncollaborative drones cannot reach. Collaborative state estimation is a task with challenging processing and latency requirements. It requires a complex interplay between communication and coordination to decide what data must be propagated to the drones in weakly covered areas. This propagation must happen in a probabilistically consistent fashion to maintain overall consistent and robust swarm-state estimation. Modular multisensor fusion[19] can be used to tackle this issue. Naive data exchange hardly scales, as every encounter with another drone requires additional bookkeeping of each other's state uncertainty. Our approach[17] linearly scales with the number of drones in the system yet shows consistent estimator behavior.

Table 1 summarizes the case studies with respect to the essential MDS building blocks.

MULTIDRONE APPLICATIONS

Multidrone applications will have a multibillion U.S. dollar market potential[20] and achieve significant socioeconomic impact.[1] However, to reach broad application, many challenges still need to be solved. They include general issues, such as security, autonomy, and robustness, but also many application-specific aspects. Table 2 compares application domains with their key performance indicators (KPIs) and states some challenges for the building blocks connectivity, communication, and coordination. Several surveys[2,3,5] provide an in-depth discussion on applications.

LESSONS LEARNED

We draw the following lessons from our experience in experimental MDS research in general and the case studies in particular.

The building blocks of MDSs are strongly application dependent

The low-level control of a drone today relies on well-established algorithms and commercial off-the-shelf components. However, developing an MDS requires an application-specific design of the high-level functional blocks due to the diverse mission specifications and differences in the drone capabilities. Suitable algorithms for reasoning, coordination, and communication must be selected individually, which requires an assessment on a case-by-case basis as to whether the relevant resource requirements can be fulfilled.

Collaborative sensing is an alternative to resource-intensive drones

The payload of aerial vehicles needs to be carefully selected. Any added weight reduces the drone's endurance and agility. Depending on the mission, lightweight drones in the MDS may be more effective and increase endurance and reachability. Such drones obtain information through collaborative state estimation from heavier drones with more capable sensors but energy-saving flight behavior.

Edge computing drives advanced drone control but requires high uplink rates

Autonomous systems can readily benefit from edge computing, for example, for vision-based drone navigation.

TABLE 2. Multidrone applications and challenges for connectivity, communication, and coordination.

Application	Characteristics and KPIs	Connectivity and communication challenges	Coordination challenges
Monitoring	Drones capture data from medium-size areas; preplanned routes with online adaptation; limited time KPI: coverage time	3D wireless connectivity; prioritized data transfer for state updates	Communication-aware, dynamic route planning; collaborative state estimation and navigation; edge computing support
Search and rescue	Heterogeneous drones explore large areas for long missions; real-time analytics; user interaction KPIs: detection time/rate; quality of service	Reliable and low-latency wireless connectivity; wide radio coverage; high-volume multimedia data transfer	Decentralized online planning; self-organized decision making; dynamic resource management
Delivery	Drones deliver goods from depots to customers; high level of autonomy; continuous operation KPIs: throughput; waiting time	Robust wireless connectivity (spoofing, jamming, and so on); secure data communication	Large-scale system optimization; continuous safety monitoring
Networking	Drones provide temporary radio access; preplanned coverage KPIs: network connections; bandwidth	Integration into existing networks; radio resource management; handovers; multitier and cross-layer network design	Demand-driven relay placement (dynamic network planning); resource management (bandwidth, energy, transmit power, and so on)
Entertainment	Drones create dynamic formations; preplanned routes; tight timing and position constraints KPIs: formation size and speed	Scalable network topology; position-aware communication	Dynamic coalition forming; collaborative positioning

High-rate uplinks are crucial in this setting, enabling fast, high-resolution image transfer to and processing on an edge server and, eventually, accurate and agile flights. Low network latency, substantial edge processing performance, and reliability are relevant as well. 5G networks are expected to provide the conditions for agile autonomous flights in the years to come.

Experimental research on MDSs is complex but worth the effort

Hands-on research with several drones is demanding but pays off in the long run. Ideally, it is carried out by an interdisciplinary team with researchers from robotics, control engineering, communication and networking, computer vision, signal processing, and software engineering. Flight operations of multiple drones must meet a wide range of regulatory and safety requirements. Research on real-world problems in actual environments provides important insights that cannot be gained by purely mathematical and simulation-based work. In this way, relevant topics are fed back into basic research.

Wireless connectivity, communication, and coordination are the building blocks to transform single drones into an MDS. Its special feature is that drones collaborate as an integrated system, where the team behavior is more important than individual actions. This collaboration provides functionality that would be impossible with individual drones. However, this feature does not come free: the building blocks must be carefully designed, taking into account their mutual interactions and the resource constraints of the drones. ◼

ACKNOWLEDGMENTS

This work was partly funded by the European Regional Development Fund and Carinthian Economic Promotion Fund for the Lakeside Labs projects Collaborative Microdrones (grant 20214/17095/24772) and Self-organizing Intelligent Network of UAVs (grant 20214/24272/36084), the Education, Audiovisual, and Culture Executive Agency of the European Commission for the Erasmus Mundus Joint Doctorate on Interactive and Cognitive Environments (grant FPA 2010-0012), the doctoral school "Networked Autonomous Aerial Vehicles" at the University of Klagenfurt, and the Austrian Science Fund (Grant P30012). We thank Agata Barciś, Michal Barciś, Samira Hayat, Roland Jung, Petra Mazdin, Jürgen Scherer, and Daniel Wischounig-Strucl for their contributions to the case studies. A part of the autonomous navigation case study was done in collaboration with Deutsche Telekom and Magenta Telekom.

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