Future Communication Applications of UAVs for Increased Resilience of Command and Control Systems

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ABSTRACT

Command and Control processes require information and information exchange among various stakeholders to function properly in large-scale disasters. Nevertheless, they also inherently rely on the existence of functioning centralized communication infrastructure. Recent disasters showcased that this infrastructure is often severely inhibited and destroyed. On the other hand, research on Unmanned Aerial Vehicles (UAVs) has shown that, e.g., they provide valuable alternatives to centralized communication infrastructure. This paper surveys the current state of the art in the practical application of command and control systems and the state of the art in research on UAV-based disaster applications. The identified lack of resilient means of communication, suitable for large-scale disasters, showcases the residual vulnerability of current command and control systems. By incorporating UAV-based communication systems into their processes the resilience of future command and control systems can be significantly increased, facilitating the necessary communication for disaster relief even when critical infrastructure fails.

Keywords

Command and Control (C2), Unmanned Aerial Vehicles (UAV), Incident Management, Communication Networks

INTRODUCTION

The availability of accurate and up-to-date information is crucial for successful decision-making and disaster response from small incidents up to large-scale disasters and crisis events (Hagar, 2015). Command and control (C2) systems are used to make information acquisition, processing and decision-making efficient and to ensure high quality in the overall incident management. A C2 system combines all processes, structures, technologies, and actors that work jointly to manage an emergency. It is, therefore, a complex sociotechnical system that is defined for efficient incident command. Therefore, the first step in all incident management processes is the acquisition and analysis of information (Ausschuss Feuerwehrangelegenheiten, Katastrophenschutz und zivile Verteidigung, 1999; Australasian Fire and Emergency Service Authorities Council, 2017; Federal Emergency Management Agency, 2017). For larger disaster events, specialized *Incident Management Teams* (IMT) and *Incident Commanders* (IC) are deployed. Their task is *information management* — collecting information, presenting it in an understandable way, and making decisions based on it — to deploy and manage rescue teams and required resources. It is apparent that time is a critical factor in incident management and the processes involved to provide fast, effective, and efficient help to the affected population (Athans, 1987; Gißler, 2021; Hagar, 2015; Lafond et al., 2017; Palen & Anderson, 2016). Furthermore, decisions must be made early enough to ensure their timeliness and not risk the operation's success due to late actions (Thomas, 1978).

Information management is especially challenging for all C2 processes involved in large-scale crises due to the problem of "getting the right information to the right person at the right time" (Hagar, 2015). In C2, this specifically addresses the information flow between IC, IMTs, and deployed rescue personnel. Information flow can be hindered

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by delays, e.g., as a result of limited transmission capacity, errors in transmission, or no available connections. Thus, decisions are often made based on incomplete information due to the substantial time pressure (Ausschuss Feuerwehrangelegenheiten, Katastrophenschutz und zivile Verteidigung, 1999). Furthermore, information can be erroneous, incomplete, or already outdated when arriving at either side, increasing the problems that need to be addressed by information management and C2.

To support IMT and C2 processes, various new technologies have been developed and implemented to quickly collect, analyze, and present information. These include, e.g., *Unmanned Aerial Vehicles* (UAV) for damage assessment in disaster areas, the automatic transmission of position and status data of vehicles, or robust radio communication channels for voice, images, and videos. However, many of the deployed and proposed technologies rely and depend on the availability of centralized communication infrastructures. If this communication infrastructure breaks down, the collection and updating of information is severely limited, if possible at all. This also means that emergency calls from the affected population can no longer contribute to the IMT's situational awareness in the event of a collapsed telecommunications infrastructure. The lack of a (sufficient) situational awareness of IMTs may lead to a false assessment of the situation and, therefore, wrong decisions.

Such a total communication failure occurred during the flood disaster in Germany in 2021. Due to the failure of the communication infrastructure, the population in the affected area was no longer able to make emergency calls, leaving them vulnerable and without the means to call for professional help. The population could also not be informed and warned effectively from official sides (Deutsches Komitee Katastrophenvorsorge e.V., 2022). Gauging stations could no longer transmit critical readings to understand the extent of the flood and react accordingly (Landesamt für Umwelt Rheinland-Pfalz, 2022). And most importantly, emergency services that had entered the affected areas could not communicate with the IMT outside and vice versa. The result was a considerable lack of coordination and operational prioritization, leading to slow and inefficient disaster relief efforts over several days (Kreienkamp et al., 2021).

To maintain effective C2 despite the failure of communication infrastructure, information acquisition and processing tools must be designed resiliently to work without such infrastructure. Additionally, they should not only include emergency services but also regard the affected population as a communication partner as well as a valuable asset for disaster relief efforts. Researchers worldwide have proposed various suitable solutions to a variety of different information management and C2 problems, that may arise in a disaster event, for years. Especially small and low-cost UAVs are a prominent topic for all communication-related research efforts, in which they have highlighted their potential. Nevertheless, such systems are still not extensively utilized today, in particular when taking Germany with its recent natural disasters in comparison. Therefore, this paper provides an overview on the C2 process, followed by the currently applied tools and systems for C2, IMT, and information management on the example of German emergency services. Afterward, different UAV-based solutions for various C2 and communication-related problems, which arise for emergency services in the face of a disaster, are discussed and categorized. Finally, we conclude with a discussion on the feasibility to include UAV-based systems in C2 processes, their benefits, shortcomings, and open issues.

INFLUENCE OF DATA AND INFORMATION IN COMMAND AND CONTROL SYSTEMS

Command and control systems are highly complex socio-technical systems in which people work together in Incident Management Teams to solve incidents and crises with the help of technology. Technology helps the IMT to process data and information efficiently, such as digitized situation maps to better present the current situation to the IMT, thus improving situational awareness. Tools for incident management are generally seen as a combination of technologies providing information gathering, information processing, and information transmission (Ausschuss Feuerwehrangelegenheiten, Katastrophenschutz und zivile Verteidigung, 1999). However, the crucial link is information transmission, as it is required to overcome long distances between IMTs and the deployed tactical units. Reconnaissance data must be transferred to the IMTs, while appropriate mission instructions based on such information must, in turn, reach the tactical units. It may occasionally be necessary to obtain reconnaissance data from deployed tactical units or to transmit instructions for action to these tactical units. The Austrian regulation for disaster management is therefore very clear: "Since without tools and technology for C2 there can be no incident management, appropriate precautions must always be taken to ensure reliability" (translated, Bundesministerium für Inneres, 2007).

Research from the C2 domain shows that C2 systems use tools to process data and information at every step of incident management. From a systemic point of view, tools for incident management are part of the physical parameters of a C2 system and, thus, form an important basis for the frictionless and efficient execution of the most important incident management process steps (Landsberg et al., 2022). In C2 research, a variety of C2 processes are examined and combined into a more generalized incident management system. Figure 1 provides a system overview

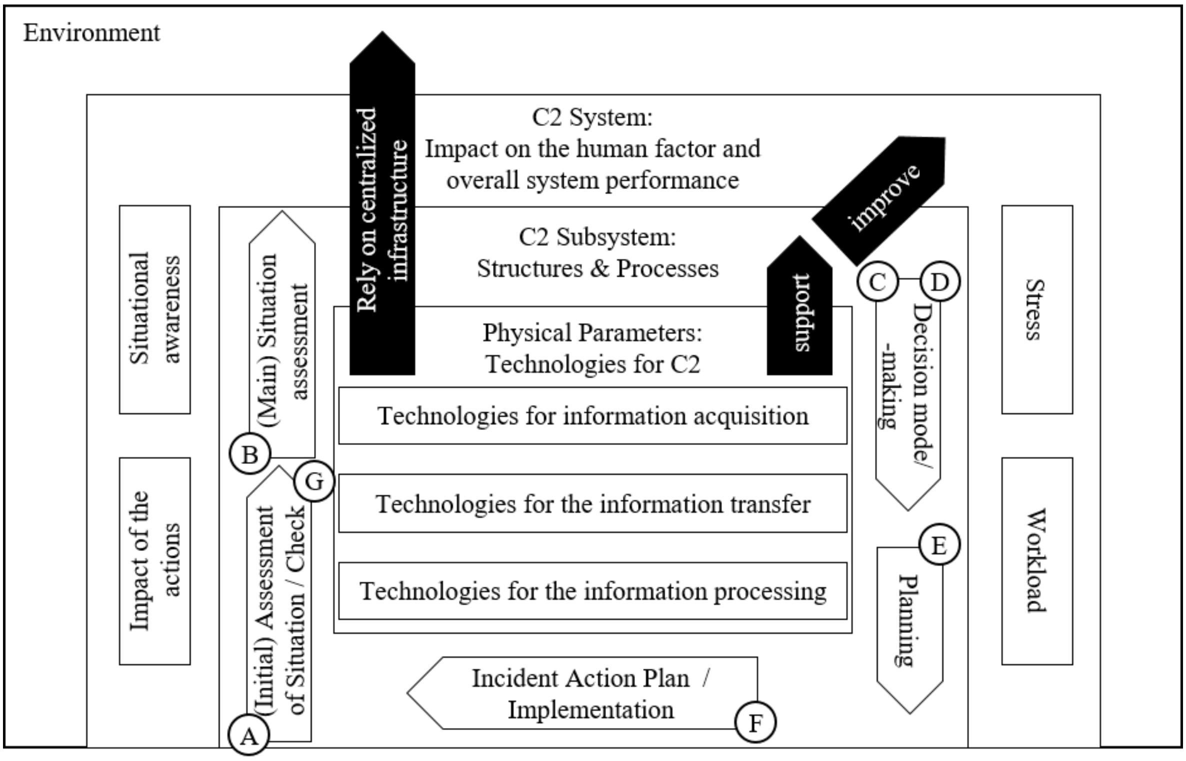

Figure 1. C2 system model, simplified (according to Landsberg et al., 2022).

and understanding of the sequential process steps. The necessary data and information to effectively support the different C2 process steps, as detailed in the following, are identified and explained on this basis.

A: Initial Situation Assessment and Response The "Initial Situation Assessment and Response" process is designed to maintain command and control, particularly in the initial phase of an operation or when rapid changes occur at short notice in highly dynamic situations. Initial information is required to provide insights into the size and impact of the incident, including possible dangers that could threaten the incident management actions. In most cases, this step involves taking mandatory measures to ensure site security and gain time for a full assessment of the situation. Possible actions in this process step include activating a suitable IMT or evacuating and shutting off a specific area. Essential data and information for this process step are generated by the initial and rapid situation assessment. Therefore, data and information that provide a quick overview of the situation are particularly helpful in this phase of the operation. This can include images and perspectives that are quickly collected, for example, from cameras, UAVs, or descriptions from emergency calls. This information must be sent to the initial incident controller as quickly as possible and displayed in a clear manner to make a rapid response to the initial situation possible.

B: Situation Assessment The second step involves comprehensively assessing the situation and sharing information with partner organizations. In particular, large-scale disasters require a wide range of organizations to work together, requiring the mutual exchange of relevant information. Therefore, information-transferring technologies are essential, or joint coordination of efforts may be difficult otherwise.

C & D: Decision mode, Decision-Making Process steps C and D build on steps A and B's information to form decisions. This includes deciding on a management style and the type of decision-making mode used for the rest of the C2 process. The management style can be, for example, people-centered or task-centered. The decision mode can be analytical or recognition-primed. Regardless of management style or decision-making mode, decision-making always requires well-prepared and cognitively straightforward comprehensible information. For easy access and organization, information can be displayed and provided in different layers on digital devices, like PCs, tablets, or phones. Very modern developments use VR glasses to display situation maps[1].

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[1] e.g., see (Strentzsch et al., 2017) or www.headwallvr.com

Initial rapid data and information on the situation	
Type	photos, videos, emergency calls, overview plans
Impact	Fast and appropriate establishment and assurance of the further ability to act and to control the incident
Transfer of information and intelligence to partner organizations and own operational units	
Type	Information on the situation, own capacities, own abilities
Impact	Increased situational awareness for all organizations and units that are part of the operation, better coordination between the organizations involved
Presentation of data and information in a suitable, well-organized, up-to-date format	
Type	digital situation maps, VR visualization
Impact	more precise understanding of the situation, effective decision-making and planning
Communication of the IAP to operating units in oral or written form	
Type	information on the current situation, orders, general conditions
Impact	support of situational awareness and mission understanding of operating units.
Transfer of data and information from the operating units to IMT	
Type	Unit location, status, on-site situation
Impact	Assessment of the effects of current commands and mission execution; precise adaptation of the IAP to the current situation.

Table 1. Important influence factors for information and data on the C2 process.

E: Planning In the planning phase, the necessary measures are planned to implement the decision of step D. To achieve this, the IMT requires up-to-date information about the available resources. Resources are tactically assigned, and an *Incident Action Plan* (IAP) is prepared for the upcoming operational period. This includes the effective organization of the chain of command and reporting channels, the preparation of orders, and the provision of logistics and administrative measures. For this process step, information on the available resources, their status, and their technical and tactical operational value must be available. As for D, this information should be as up-to-date and visually well-presented as possible. This is possible, for example, through the automated transmission of data from tactical units.

F: Implementation During the implementation phase, the IAP is distributed to the operating units and tasks are assigned for the operation. The distribution of the IAP is also intended to provide the operating units with the necessary situational awareness. The IAP, therefore, also provides information about the context of the assigned task in the overall operation, about all the relevant frameworks, such as logistics and communication, and about special circumstances and hazards. The IAP can be communicated verbally or in written form, depending on the situation. However, written communication is particularly useful for large operations as much information must be conveyed, understood, and memorized. This phase of incident command also shows that the transmission of data and information is an important part of the C2 process. The executing units must be reliably informed about their orders and the framework conditions if they are geographically remote to ensure that the plan developed by the IMT is effectively implemented.

G: Check The last phase of the C2 process checks the fulfillment and effects of the orders given. This includes whether the operational units have reached their appointed area of operations, have sufficient resources to carry out the mission, and whether the planned measures show the expected effect. The requirements for this process step show that information must be transmitted, particularly from the operating units to the IMT. This information includes location, status, and situation data.

Summary Each phase of the C2 process demonstrates that the transmission and presentation of information is critical to efficient incident management. Fast transmission and clear presentation of relevant data make it possible to understand the situation more quickly, coordinate, make decisions, plan more precisely, and delegate tasks to the operating units more effectively. Table 1 provides an overview of the most important influence factors on the C2 process of data and information in disaster management.

EXISTING TOOLS FOR ACQUIRING AND PROCESSING INFORMATION

For every C2 process step, there are existing tools that have dependencies on centralized communication infrastructure. The standard emergency call can be transmitted via cell phone or network telephone. Only if the necessary infrastructure exists and is intact is it possible to transmit information about disasters or crises from the affected population to the incident control center and to the IMT. Without this possibility, no valid situational picture can be established in the event of disasters. For example, the telecommunications network failed during the severe flooding disaster in 2021 in Germany (Deutsches Komitee Katastrophenvorsorge e.V., 2022). Since many emergency call apps, camera systems, or sensors also send data via a centralized telecommunications infrastructure, these options for developing the situation picture are also lost if centralized structures are destroyed. There are also applications that support situation assessment or first aid by leveraging smartphone cameras of citizens in the immediate vicinity of the affected region, sending photos or videos to the control center and the IMT (Ecker et al., 2021). Of course, this support also requires an existing and functioning cellular network. During the 2021 flood disaster, for example, it was no longer possible to transmit current water levels to the IMT, which gave the false impression that the water levels were no longer rising (Landesamt für Umwelt Rheinland-Pfalz, 2022). Thus, the first phases of the C2 process are particularly restricted if communication infrastructure fails and important situational information from certain regions is missing.

Collaboration between several IMTs from different organizations also requires the use of a centralized telecommunications infrastructure. Especially if the IMTs are physically separated from each other (Berggren et al., 2014). Digital means of communication such as e-mail, voice over IP or digital online conferences are often used for the mutual exchange of information. Without a proper exchange of information, the strengthening of mutual situational awareness is weakened and the coordination of joint efforts is made more difficult.

Today, the status of resources and the situation reports of these resources are usually transmitted via TETRA digital radio (Liu & Li, 2023). Analog radio communication is provided as a fallback level, but this is also dependent on radio masts and relay stations, respectively. Very modern approaches enable the continuous and automated transmission of the location and relevant data on resources, material, and personnel of a tactical unit via cellular mobile networks (“ZF Rescue Connect: Digitale Lösungen für Einsatzkräfte”, 2025). This information is used to create a picture of the resource situation and the impact on site. Without the ability to transfer this information from the deployed units, the situation picture of the resources and the impact is not updated for the IMT.

In addition to the connection of the operating units to the IMT, the opposite connection is also necessary. The IMT must be able to give orders to the deployed units and communicate information about the situation. The state of the art here is also the use of digital or analog radio channels and verbal communication. Advanced approaches use digital devices to communicate mission data, reducing verbal communication to a minimum (Usbeck et al., 2015). All of these communication channels rely on centralized communication infrastructure. If this does not work, deployed units cannot be controlled in line with changes in the situation.

In recent years, the active utilization of *Unmanned Aerial Vehicles* (UAVs) has found its way into emergency services. UAVs offer a quick way of obtaining live image and video data from a bird’s-eye view, often used to provide a constantly updated situation picture. Nevertheless, the possible tasks of UAVs are much broader than just the transmission of videos and images, encompassing reconnaissance, documentation, search and rescue, transport of material, and the detection and tracking of hazardous substances (German Federal Office for Civil Protection and Disaster Assistance (BBK), 2024). A common categorization of UAVs is made between plane-like *fixed-wing UAVs* and helicopter-like *rotary-wing UAVs*. Fixed-wing UAVs are better suited for extended flights at constant speed and carrying heavier payloads, but they require extensive dedicated spaces for takeoff and landing. In contrast, rotary-wing UAVs can hover and feature *vertical takeoff and landing* (VTOL) capabilities, making them easier to control and more practical for urban environments and for tasks where hovering over a fixed location is required (Namuduri et al., 2018). The choice of which UAVs to use and how is mostly based on the designated task or application (Erdelj et al., 2017; German Federal Office for Civil Protection and Disaster Assistance (BBK), 2024).

However, these systems typically rely on radio technologies like WiFi to connect a single UAV to a single receiving control device on the ground, providing only limited range for small and geographically limited incident sites. For larger disasters and multi-UAV deployments, the application of current UAV systems would require an available centralized communication infrastructure or would rely on satellite-based *Non-Terrestrial Networks* (NTN) (Hosseini et al., 2019). While the former may not be available in a disaster scenario, as shown in the example of the 2021 floods in Germany, the latter may not be possible, e.g., due to the weight and costs of UAV-NTN interfaces.

Another issue is the integration of UAVs into the common airspace and its regulations, which were specified primarily for crewed aircraft[2]. Despite some regulatory adaptions, UAV flight is typically prohibited by night,

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[2] Although Article 8 of the ”Convention on International Civil Aviation” of the *International Civil Aviation Organization* (ICAO) from 1944 already addressed pilotless aircraft. Cf. https://www.icao.int/publications/documents/7300_orig.pdf

beyond visual line-of-sight, and without an active pilot (European Aviation Safety Agency (EASA), 2008; Federal Aviation Administration, Department of Transportation (FAA), 2020; International Civil Aviation Organization (ICAO), 2011). This restricts already existing capabilities for autonomous flight that are necessary for large-scale deployments, both in terms of covered space and the number of deployed UAVs. Programs, such as the FAA's BEYOND[3] program in the U.S., allow limited autonomous or beyond line-of-sight remote-piloted applications for research and testing purposes, but the regulatory integration of UAVs is a slow-running process (International Civil Aviation Organization (ICAO), 2011). Although not within the scope of this paper, the adaptation of regulations to future emergency service applications of UAVs is as important as its technical feasibility.

Overall, the currently applied UAV systems face challenges similar to all other C2 technologies, mostly a considerable dependence on available centralized communication infrastructure. In the following, we present and discuss the state of the art for UAV-based systems that specifically address these challenges.

RESEARCH PERSPECTIVE ON UAV-BASED DISASTER APPLICATIONS

When considering larger deployments of Unmanned Aerial Vehicles (UAVs), these applications typically exceed just a single UAV and a pilot using a remote control. In this case, the term UAV-based system or, more commonly, *Unmanned Aerial Systems* (UAS) is used — describing a complex system of (multiple) UAVs and ground-based hardware for maintenance, communication, and operation, thus, directly including C2 as part of the aerial system. Especially UASs with autonomously operating UAVs are a frequent topic of interest in diverse research areas on disaster relief, as discussed later.

Primarily, research focuses on small-sized UAVs[4] which are commercially available or can be constructed out of commercially available components. These UAVs are generally equipped with an onboard flight computer, a GNSS[5] system, and small onboard sensors and cameras. As discussed before, the applied UAVs can be typically categorized into two main types: plane-like *fixed-wing UAVs* and helicopter-like *rotary-wing UAVs*, each with their specific fields of application (Erdelj et al., 2017). Although recent advancements have led to the development of hybrid and convertible UAVs, which aim to combine the energy efficiency of fixed-wing flight with the superior controllability of VTOL-capable systems[6] these are not commonly used at this time. Currently, rotary-wing UAVs of a few kilograms and around 30 minutes flight dominate the category of small UAVs in research for civil and emergency service applications.

Key research areas in UAV applications directly related to C2 systems and processes include Search and Rescue (SAR), path planning and placement, (visual) detection, disaster networks, and communication. Adjacent research areas, but not within the scope of this paper, encompass the safe integration of UAVs into civil air traffic, cybersecurity of UAVs and their operation, as well as privacy and security of data stored on the UAVs and exchanged within the system (Müller & Bauer, 2024; Tsao et al., 2022; Zieher et al., 2024).

In the following, we categorize state-of-the-art research into two larger sets. The first category encompasses *reconnaissance and monitoring* applications that are directly applicable to C2 processes and systems for information acquisition. The second category encompasses *aerial communication systems*, which are specifically tailored to enable communication inside and over the boundaries of a disaster area without a working communication infrastructure. Similar to most disaster-related applications, neither reconnaissance nor communication tasks are exclusively deployable and cannot be performed absolutely independently from each other. Information from reconnaissance is necessary to set up and maintain functioning communication systems, while communication is required for an efficiently performing reconnaissance system. Although both tasks could be executed on the same UAVs simultaneously, previous work has shown this leads to very poor performance for at least one of the tasks due to severe differences in the UAV mission goals for each task. Separating mission profiles and deploying dedicated UAVs for each task is much more efficient, more performant, and can be executed adaptively and optimally within a single UAS (Zobel, 2023). Therefore, such a UAS can significantly benefit the overall performance and resilience of C2 systems, especially for unknown and constantly changing disaster situations.

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[3] https://www.faa.gov/uas/programs_partnerships/beyond

[4] Note that there is no unified definition of 'small UAV'. Research addresses this typically with weights below 5kg (or lightweight; usually can be carried by a person), maximum allowed altitudes around 100m, 20-60 minutes flight time or a few kilometers in range — these properties are similar to well-known commercially available UAVs. Regulatory bodies like the U.S. *Federal Aviation Administration* (FAA) or the *European Union Aviation Safety Agency* (EASA) categorize small UAVs as less than 25kg, but provide a more fine-granular sub-categorization with specifications and regulations within. In summary, regulations are less strict for UAVs below a few kilograms in weight, thus favoring this for research or private activities.

[5] Global Navigation Satellite System, e.g., GPS (USA), GLONASS (Russia), Galileo (European Union), BeiDou (China).

[6] see, for example, Wing Aviation LLC https://wing.com/

Reconnaissance and Monitoring Applications

Since their active introduction into emergency services, reconnaissance and monitoring applications have been the predominant use case for UAVs. Their aerial viewpoint and their overview provision to rescue personnel and IMTs on the ground is absolutely valuable.

Having started with a simple camera feed sent to the pilot's monitor on the ground, state-of-the-art research addresses the efficient utilization of one or multiple autonomously acting UAVs that visually map a disaster area with their cameras and provide a mosaic picture of it (Aljehani & Inoue, 2019; Cabreira et al., 2018; Mersheeva & Friedrich, 2015; Quaritsch et al., 2011; Reinoso et al., 2018; Rémy et al., 2013; Yanmaz et al., 2018). These overview pictures can then, for example, be automatically processed to detect humans in it (Heemskerk et al., 2024). By adding further sensors, UAVs can also be used to detect, measure, and monitor contaminants in the air (Allred et al., 2007; Daniel et al., 2009; Euler & von Stryk, 2017).

Search and Rescue (SAR) operations are also a well-researched application field. These include, e.g., the detection of missing persons based on their garments, the autonomous tracking of moving persons, or the detection of persons trapped under debris (Arafat & Moh, 2021; Bi et al., 2016; Hayat et al., 2020; Rémy et al., 2013; Tobergte et al., 2022). Some research also addresses the problem of a lack of centralized communication infrastructure, facilitating the multi-UAV SAR system to reposition the UAVs to form a chain-like relay network between the tracking UAV and the operator (Scherer et al., 2015).

A major problem is that mapping and SAR approaches heavily rely on cameras and visual identification. Nevertheless, disaster areas are typically not plain open areas; obstacles such as trees may block the line of sight, and people may be inside buildings. Therefore, additional methods to identify persons without a proper line-of-sight are researched. These focus on radio wave detection from typically carried devices like smartphones, predominantly for WiFi and cellular frequencies. They have shown to be applicable under adverse conditions, allowing detection even within buildings or under rubble (Abrajano et al., 2017; Carpin et al., 2015; Rubina et al., 2019; Zeng et al., 2019). Other radio technologies such as LoRa have also shown to be usable for detection (Lin et al., 2019; Solpico et al., 2019), but are rarely used in the general population.

The feasibility of UAS applications in large-scale disaster scenarios requires the *Coverage Path Planning* (CPP) problem (Di Franco & Buttazzo, 2016; Y. Li et al., 2011) to be addressed. Usually, all reconnaissance and monitoring applications want to have information on the entire disaster area, and leaving out parts would lead to blind spots for IMTs (Almadhoun et al., 2019). Available heuristics cannot guarantee full area coverage and, thus, are suboptimal to use for such missions (Sánchez-García et al., 2019; Wang et al., 2019). The goal of traversing the entire disaster area in detail quickly leads to route lengths and flight times exceeding the technical capabilities of single UAVs. Deploying multiple UAVs is, therefore, necessary. However, calculating optimal (or at least good) paths for multiple UAVs is computationally complex to calculate and requires appropriate hardware (Apostolidis et al., 2022; Hayat et al., 2020). It may also lead to inefficient usage of available UAVs (Araujo et al., 2013; Y. Li et al., 2011), which need to be considered when planning UAS deployments.

Besides route calculation, further operational issues arise for the IMTs. For one, the increased flight times delay the reception of the reconnaissance information without a proper long-range communication link or without an available communication infrastructure (citation redacted for blind submission). This again defers a possible start of rescue missions or reactions to newly developing situations due to delayed situational awareness. Furthermore, increased flight times also increase the risk that situations change after they have been monitored by the UAV but before they are delivered to the IMTs, increasing the risk of wrong assessments. Secondly, the number of required UAVs to maintain an acceptable performance increases considerably with larger disaster areas, partly due to the aforementioned issue. Not only are more UAVs generally needed to monitor a larger area in parallel, but more are also needed when IMTs need to have faster results delivered. Furthermore, this does not include surplus UAVs to cover possible hardware failures or to compensate for battery loading and replacement (Erdelj et al., 2017).

In conclusion, advanced reconnaissance and monitoring applications were proposed by research that would greatly benefit C2 processes. Open research issues, like routing optimization for multi-UAV deployments or combining different reconnaissance methods to overcome problems with pure visual detection, are no threat to the practical feasibility. However, emergency services must be prepared to provide sufficient UAVs and supporting hardware for efficient large-scale and long-term deployments.

	Aerial Networks	**Aerial Data Ferries**
Task	Infrastructure replacement	Data transfer between communication islands
Opportunities	Concurrent network coverage of the civilian population, applicability beyond pure C2 system networking possible	High adaptivity to fast-changing network situations, suitable for initial deployment directly after a disaster event
	Parallel monitoring of the covered area without additional dedicated monitoring units possible	Dedicated communication between emergency teams, but extendable to integrate civilian communication islands
	Replacement of communication infrastructure without requiring changes in C2 systems or end devices	Combination of multiple communication technologies possible, but low cost and low resource usage
Challenges	Significant resource requirements (number of UAVs, supporting hardware and personnel, costs of acquisition and maintenance)	Monitoring information requirements (limited applicability without information on the location of communication islands)
	Achieving and maintaining network coverage (Optimal placement, UAV replacement)	Optimal routing, minimal communication delays (Travelling Salesman Problem)
	Adaptivity to fast-changing situations	Integration of delay-tolerant networking paradigm in C2 systems

Table 2. Overview on the most prevalent opportunities and challenges of integrating UAV-based communication applications in command and control systems, categorized for aerial networks and aerial data ferries.

Aerial Communication Systems

Especially in recent years, the application of UASs as surrogate *Aerial Communication Systems* (ACS) has received considerable attention. More and more, UAV-based deployments are specifically considered for early disaster scenarios because they can quickly fly over impassable terrain like collapsed bridges and debris (Bundesamt für Bevölkerungsschutz und Katastrophenhilfe (BBK), Germany, 2022; Erdelj et al., 2017; Lieser, Zobel, et al., 2019) before any ground-based systems such as mobile cellular radio or satellite stations can be deployed. Furthermore, a UAS provides superior system adaptivity in dynamic environments and faster deployments in comparison to ground-based communication equipment that requires static setups in the disaster area as well as costly hardware and skilled personnel (Baumgärtner et al., 2016; Eiselt & Marianov, 2012; Gardner-Stephen et al., 2013). For most ACS, smaller multi-rotor UAVs are the predominant choice, not only due to their easier usage but especially because of their hover capability: holding position increases communication performance (Mozaffari et al., 2017; Namuduri et al., 2018) in comparison to constant movement of fixed-wing UAVs, as antenna movement and changes in antenna orientation worsens radio connectivity (Asadpour et al., 2013; Bujari et al., 2017).

Aerial communication systems can be categorized into two major categories: (i) aerial networks and infrastructure replacement and (ii) data ferrying between separated communication islands. Both serve different application scenarios, bringing individual benefits, drawbacks, and requirements. Similarly, the utilized communication technologies must be chosen appropriately to the intended application, the provided services, and the devices served on the ground (Zeng et al., 2016). Table 2 summarizes the most prevalent opportunities and challenges for both categories, which are discussed in detail in the following.

Aerial Networks and Infrastructure Replacement

The first category encompasses approaches with the main goal to replace the damaged or broken infrastructure within the disaster area. In most cases, this means providing cellular service coverage, e.g., 5G (Zeng et al., 2019), by placing UAVs as cellular access points, similar to normal cell towers. With partially available infrastructure, a few UAVs can take workload from overloaded cell towers and compensate localized outages (Merwaday & Guvenc, 2015; Naqvi et al., 2018). Similarly, UAVs can extend the range and connectivity of the cellular network, acting as a relay between users and the actual cell tower (Caillouet & Razafindralambo, 2017; X. Li et al., 2015; Mori et al., 2015; Saha et al., 2015). Most often, however, it may be necessary to replace the cellular network completely. Utilizing a large number of UAVs as a swarm, individual UAVs serve as radio access points to the devices on the ground while, overall, forming a mesh network over the disaster area (Esrafilian et al., 2020; M. Gupta & Varma, 2021; Mahoro Ntwari et al., 2021; Sabino & Grilo, 2018). The mesh network can also connect to the outside when cellular towers are working on the edge of the disaster area (Chakraborty et al., 2018; Moradi et al., 2018).

Utilizing aerial networks as a replacement for broken cellular infrastructure is beneficial not only to IMTs and C2 systems but also to the affected civilian population, allowing all users on the ground to transparently use their accustomed services (Esrafilian et al., 2020; M. Gupta & Varma, 2021; Mahoro Ntwari et al., 2021; Sabino & Grilo, 2018). Furthermore, communication over the mesh network may be quick and performant, providing service quality similar to normal infrastructure, especially when covering the entire area (Kuperman et al., 2014). Nevertheless, this comes with a huge price since the number of required UAVs to cover large-scale disaster areas may be enormous. Research provides approaches to address such limitations and other requirements, e.g., by finding an optimal placement for coverage with a limited number of UAVs (Hu et al., 2020; Mahoro Ntwari et al., 2021), optimal placements with environmental restrictions (Esrafilian et al., 2020), or even placements with regard to Quality-of-Service requirements (Caillouet & Razafindralambo, 2017; Sabino & Grilo, 2018). A remaining open issue is the adaptivity of such results. Most work only considers the static placement of UAVs without further assessment for changes in the disaster situation or without incorporating the mobility of devices on the ground. However, the constant re-evaluation and adaptation of aerial networks is a clear necessity for the proper long-term functionality of the system (M. Gupta & Varma, 2021; Zobel, 2023).

Another option is to provide aerial networks only for emergency services and their operating locations, which reduces the number of required UAVs. This would also be necessary if the applied C2 systems do not work with or use cellular services but may require, e.g., their own WiFi-based network (Abrajano et al., 2017). Direct interaction with the emergency services' TETRA network would also be possible with the appropriate UAV hardware (Kukliński et al., 2022). Similarly, connectivity for C2 could be increased by integrating UAVs and NTNs (Liang et al., 2024).

Overall, aerial networks can provide communication capabilities for C2 systems, emergency services, and the population in a disaster area. Aerial networks with extensive coverage could also be extended with monitoring capabilities, combining networking and monitoring in a single UAS. However, achieving sufficient service quality is an enormous task due to the number of required UAVs and supporting hardware.

UAV-based Data Ferrying between Communication Islands

To address the issue of overwhelming numbers of UAVs to facilitate communication within a disaster area, the concept of data ferrying was introduced. In contrast to setting up a static overlay network in the area, data ferrying makes use of the UAVs' high mobility, independent of blocked roads or broken bridges, to physically transport information between separated communication partners or between independently working, remaining infrastructure (X. Li et al., 2015; Mori et al., 2015; Saha et al., 2015). Sparsely populated areas are usually not served specifically. Data ferrying is especially suitable between known and fixed locations, e.g., between towns, shelters, or IMTs and their operating personnel, covering large areas with limited numbers of UAVs (Erdelj et al., 2017; Lieser, Zobel, et al., 2019; Zeng et al., 2016).

However, the physical information transport introduced a considerable delay in communication, similar to long-term mapping without a direct communication link. Utilizing multiple UAVs is, therefore, beneficial — but still with significantly fewer UAVs necessary than for an aerial network. Another drawback is that data ferrying cannot be integrated into normal communication networks as easily as a simple overlay network since normal routing mechanisms cannot cope with the considerable delays. *Delay-Tolerant Networking* (DTN) must be employed instead, which requires, for example, specific apps on smartphones or built-in mechanisms in C2 systems (Álvarez et al., 2018; Meurisch et al., 2017). The concept of DTNs is, however, simple, robust, and facilitates communication over different radio technologies at the same time (Baumgärtner et al., 2020; Torgerson et al., 2007).

Research usually focuses on optimal routing for UAVs, i.e., finding the shortest and fastest path between all users (Abrajano et al., 2017; Lagazo et al., 2018; Lieser, Zobel, et al., 2019; Mozaffari et al., 2017; Qin et al., 2019). Also known as the NP-hard *Travelling Salesman Problem* (TSP), finding one optimal route or the optimal routes for multiple UAVs is no simple endeavor (Messous et al., 2016; Qin et al., 2019), especially when adding complexity, e.g., by information delivery deadlines, message prioritization, or obstacle avoidance (Y. Li et al., 2011; Lieser, Richerzhagen, et al., 2019; Sepúlveda et al., 2021). Thus, most approaches rely on heuristics for UAV routing with many places to visit (Balas & Christofides, 1981; Bonomi & Lutton, 1984; Cormen et al., 2009; L. Gupta et al., 2016; Ray et al., 2007).

Nevertheless, routing does not pose a significant problem for UAV applications in C2 systems, as absolute performance optimization is usually not the main objective. Research provides a multitude of different approaches to UAV-based data ferrying, which facilitates communication between IMTs and their personnel, between different IMTs, or generally many stakeholders in large-scale disaster scenarios. In the end, DTNs with store-carry-forward UAVs provide resilient communication for C2 systems with reasonable resource requirements.

CONCLUSION

In this paper, we detailed the different command and control processes for incident management and highlighted their reliance on descriptive, up-to-date, and accurate information. Despite nearly 20 years of research for alternatives, C2 systems still rely heavily on available, centralized communication infrastructures to exchange information. Recent examples show that even well-functioning, modern C2 systems quickly reach their limits when these means of communication fail. A lack of communication renders efficient incident management impossible, as IMTs cannot determine the situation, and operating units cannot be organized and commanded.

On the other hand, research in the field of UAV disaster applications is manifold. This paper discusses various reconnaissance and monitoring applications, aerial networks for the replacement of communication infrastructure, and resource-efficient data ferrying applications via UAVs. All these applications provide valuable concepts to increase the resilience of C2 systems and directly support disaster relief efforts of IMTs and emergency services. The currently increasing usage of UAVs for reconnaissance and monitoring in C2 processes is a necessary step towards progress. Nevertheless, these UAV-based systems, being a part of the C2 process, also do not address a possible lack of a centralized communication infrastructure, thus, inheriting the same problems without communication capabilites like the rest of the C2 system. Furthermore, the currently deployed UAV systems remain mostly small in scale and are being remotely piloted. The use of — already available — autonomous flight capabilities would not only greatly increase the deployment scale and the area of operation, but also relief ground personnel.

In conclusion, a functioning, resilient C2 system cannot solely rely on a centralized communication infrastructure. Communication applications based on UAVs provide suitable alternatives to maintain communication in C2 systems even when critical infrastructure fails. With the tremendous challenges of increasingly impactful natural disasters ahead, which starkly contrast our society's reliance and dependency on fast and always-available means of communication, it is now the time to adopt solutions from research into C2 systems to increase their reliability, efficiency, and resilience in the future.

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All web pages and URLs used in this work have been checked in February 2025. However, due to the dynamic nature of the World Wide Web, their long-term availability cannot be guaranteed.