Help from the Sky: Leveraging UAVs for Disaster Management

This survey of advances in unmanned aerial vehicles (UAVs) for network-assisted first response to disaster management covers disaster prediction, assessment, and response, presenting network architectures for geophysical, climate-induced, and meteorological disasters based on interaction between the UAV and wireless sensor network.

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Large-scale natural disasters test the most fundamental human instinct of survival by inflicting massive and often unpredictable losses of life and property. Various types of natural disasters, such as *geophysical* (earthquake, tsunami, volcano, landslide, and avalanche), *hydrological* (flash-floods, debris flow, and floods), *climatological* (extreme temperature, drought, and wildfire) and *meteorological* (tropical storm, hurricane, sandstorm, and heavy rainfall), have resulted in the loss of many lives. There has also been an increase in material losses caused by such disasters on the order of 100–150 percent over the past 30 years.[1] Many efforts are underway to recognize and forecast the occurrence of natural disasters to help us react in a timely manner and quickly and efficiently assess the damage, address the outages, and restore normalcy.

Acknowledging the need for bolstering disaster resilience, here we describe a vision for leveraging the latest advances in wireless sensor network (WSN) technology and unmanned aerial vehicles (UAVs) to enhance the ability of network-assisted disaster prediction, assessment, and response. When a disaster occurs, the most important issue is preserving human lives. In this context, the first 72 hours after the disaster hits are the most critical, which means that search and rescue (SAR) operations must be conducted quickly and efficiently. The major problem is the lack of communication and situational awareness during a disaster, forcing first responder teams to improvise and thus degrading the efficiency of the rescue mission.[2]

This article reviews the latest advances in UAVs for network-assisted first response to disaster management and identifies open issues that need to be solved. In particular, we present an approach for classifying disasters, and we outline suitable network architectures for effective disaster management based on these classifications.

UAV-Assisted Disaster Management

The response time of disaster management personnel during a natural disaster is key in saving the lives of those in the affected areas. The most efficient situational awareness is achieved through aerial assessment—UAV networks. Different regulations apply to the usage of UAVs, depending on the country, but during a disaster, special authorizations are usually granted to flying devices to help first responders assess the situation as quickly as possible.

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Using UAVs, first responders can better understand which structures were affected by the event, the extent of the damage to these structures, the state of the transportation infrastructure, and the potential number of people affected by the event. However, the UAV network can't efficiently cope with issues of power supply limitations, processing-power limitations, unreliable communication channels, unexpected node failures, maximal physical load size, and maneuverability in harsh conditions.[3]

The need for real-time knowledge in driving SAR missions can't be underestimated, and a recent Red Cross report advocates for UAVs as one of the most promising and powerful new technologies for this purpose.[4] From their high vantage point, teams of UAVs can provide reconnaissance and mapping support; perform structural assessment; identify stranded survivors and direct them to safe locations; and serve as an ad hoc communications infrastructure to connect mobile devices to the nearest radio access network (RAN), relying on different types of UAVs, such as blimps, balloons, and fixed-wing and rotary-wing UAVs.[5]

Features of UAV Networks

Although the UAV can play a powerful role in a disaster scenario, naively launching multiple UAVs won't guarantee a successful SAR mission. This article delves into some critical aspects of the network design, which differ from classical sensor networks. In particular, the UAV network must accommodate the following.

Energy-effectiveness tradeoffs. Currently available off-the-shelf UAVs can remain airborne for approximately 15–20 minutes at a time. Thus, their mission must be highly optimized, and suboptimal topologies with reduced movement might actually result in longer-lived, more successful missions.

Dynamic topologies. Theoretical or a priori placement optimizations done centrally might not translate to the same exact locations in the corresponding 3D airspace. Unpredictable air drafts, inaccuracies in the 3D channel models, and on-field changing conditions can require sudden and unanticipated changes in UAV localization. Protocols that rely on next-hop forwarding, link-layer retransmissions, and error control, among other approaches, must adjust to these situations in real time.

Multi-objective downtimes. Given the energy demands, UAVs engaged in SAR functions require multiple rounds of recharging. Each such downtime recalls the UAV to the nearest charging center, which raises interesting questions regarding whether the same network can be maintained (by introducing redundancy) or the entire topology must be proactively changed (at the cost of performance).

Applications of UAVs

UAVs have been used in many different disaster management applications,[6] but mostly for the following:

- *Monitoring, forecasting, and early warnings*—using structural and environmental monitoring and analyzing information for forecasts, UAVs can act as early warning systems (EWSs).
- *Disaster information fusion and sharing*—by combining different sources of available information or providing a bridge between different information technologies, UAVs can support other applications during disaster management.
- *Situational awareness and logistics and evacuation support*—UAVs can help gather information during the disaster phase, especially regarding the movement of affected people and deployed rescue teams.
- *Standalone communication system*—UAVs can re-establish the damaged or destroyed communication infrastructure during the disaster.
- *SAR missions*—UAVs can search for and rescue people lost, injured, or trapped by debris.
- *Damage assessment*—UAVs can help assess the damage though different methods, such as structural health monitoring and UAV video inspection.

In addition, the following set of disaster management applications could be managed more efficiently with the use of UAVs:

- *Media coverage*—UAVs could help deliver timely information to viewers for informational purposes (in contrast to providing situational awareness for rescue teams).
- *Medical applications*—although restrained in the means of payload weight, specialized drones could automatically deliver supplies essential to keeping people alive, even in the case of a destroyed transport infrastructure with cut-off roads.
- *Infrastructure (re)construction*—using a network of UAVs could speed up the process of inspections and improve the efficiency and precision of infrastructure reconstruction.

The research community hasn't sufficiently studied these application areas, and we hope these areas receive more attention in the near future.

UAV Usage in an Example Scenario

In an example scenario of UAV usage for disaster monitoring, we propose having UAV stations equipped with fixed-wing and rotary-wing UAVs. Specifically, we propose using a fixed-wing UAV that can quickly survey the disaster area. Once people or vehicles have been detected,[7] quadcopters can be sent to these critical spots to gather the real-time information. (See Table 1 for a list of different drone types and their characteristics.)

Assuming a quadcopter with 20–25 minutes of airborne operation duration and 60–80 minutes of battery charge duration is used for the monitoring task, we estimate needing four UAVs per position, but we'd add an extra

TABLE 1
Various types of drones.

Drone type	Pros	Cons	Application	Price range (US$)
Fixed-wing	Large area coverage	Inconvenient launch and landing Price	Surveying an area, structural inspection	$20,000–$150,000
Rotary-wing (helicopter)	Hover flight Increased payload	Price	Aerial inspection, supply delivery	$20,000–$150, 000
Rotary-wing (multicopter)	Availability (price) Hover flight	Low payload Short flight duration	Aerial inspection, filmography, photography	$3,000–$50,000

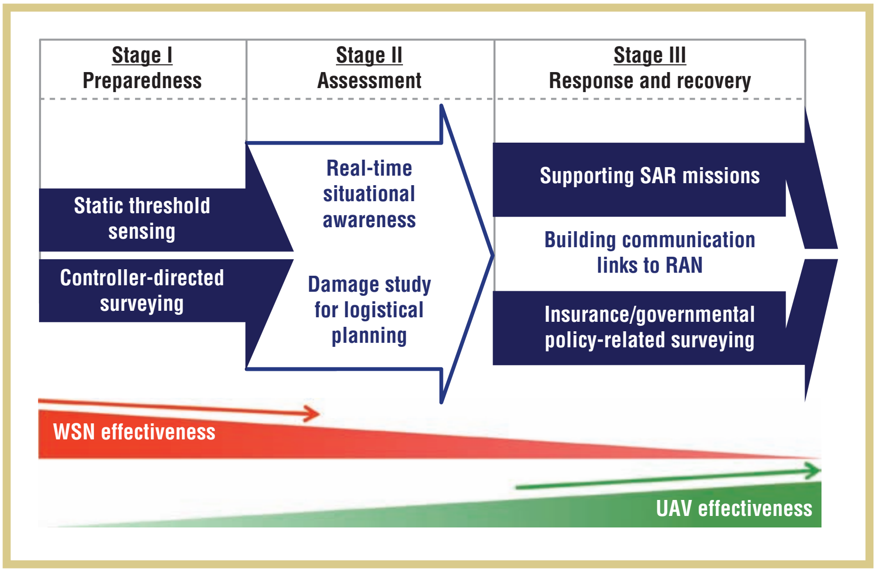


Figure 1. Disaster stages and UAV-assisted operations. As the disaster stages progress, static wireless sensor network (WSN) deployments become less effective.

UAV for sufficient redundancy in constant surveillance. A fixed or mobile first-response UAV station should thus be a vehicle that can store at least five quad-copters and one fixed-wing UAV and is equipped with a long-distance communication antenna, an electricity generator, and a system for automatic UAV battery recharging. The mobile UAV station could be operated by a single human operator, mostly to maintain the station and to act as a safety supervisor if something goes wrong during the UAV network operation. This kind of UAV station could also implement an approach for automatic battery replacement,[8] together with an approach for vision-based formation control[9] to allow a simplified yet effective control of a group of UAVs. We assume that the system can rely on the GPS positioning, while the operator can manually correct the hovering position of a UAV based on multimedia input.

Commercial UAVs should be used for disaster management because of their availability, affordability, and ease of use. Once our proposed approach for disaster management involving commercial UAVs has been implemented, it's possible that future applications could employ even more powerful and durable quadcopters and fixed-wing UAVs. Although the cost of such applications might be significantly higher, that investment would be justified by improved reliability and robustness.

Disaster Stages

Figure 1 shows our proposed operational lifecycle for UAVs participating in natural disaster management. The lifecycle comprises three stages:

1. *Pre-disaster preparedness*—UAVs survey related events that precede the disaster, offer static WSN-based threshold sensing, and set up an EWS.
2. *Disaster assessment*—UAVs provide situational awareness during the disaster in real time and complete damage studies for logistical planning.
3. *Disaster response and recovery*—UAVs support SAR missions, forming the communications backbone, and they provide insurance-related field surveys.

Each stage imposes a set of UAV task demands of different lengths of time and with varying priority levels.

We argue that a single optimized but static network for all three stages is no longer sustainable; rather, the network must continuously evolve in topology and capability. As the disaster stages progress, and as is evident from the typical functions involved as shown in Figure 1, static WSN deployments become less effective.

Figure 2 provides a classification of these disaster stages and possible related activities, based on the disaster type, which we outline as follows:

- type A: geophysical (earthquake, tsunami, volcano, landslide, avalanche) or hydrological (flash-floods and debris flow);
- type B: climatological (extreme temperature, drought, wildfire), hydrological (floods), or human-induced (industrial hazard, structural collapse, power outage, fire, hazardous material contamination); or

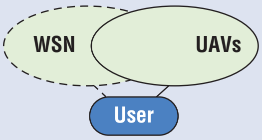
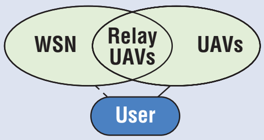
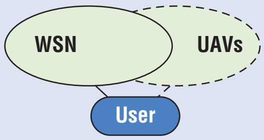
Disaster stages	Disaster type and impact on technology					
	Type A: Geophysical or Hydrological		Type B: Climatological, hydrological, or human-induced		Type C: Meteorological	
	WSN not operational UAVs fully operational 		WSN partially operational UAVs fully operational 		WSN fully operational UAVs partially operational 	
Preparedness: Monitoring and surveying Early Warning Systems (EWS)	WSN with limited UAV roles					
	Different types of wireless sensors are statically deployed in the potential disaster area An occurrence of a disaster triggers WSN reporting with optional UAV support					
Assessment: Situational awareness Damage assessment Structural inspection	No WSN	UAV	Partial WSN	UAV	WSN	No UAV
	Damage assessment and structural inspection is being done by UAVs		Damage assessment is done by UAVs, backed up by the operational part of WSN		WSN information fusion for situational awareness	
Response and recovery: Rescue missions Supply delivery Communication system	No WSN	UAV	Partial WSN	UAV	WSN	No UAV
	Sensing, monitoring, SAR, and communication restoration is being done by UAVs		UAVs restore the broken connectivity and SAR operations using a combination of WSN and UAVs		Integration of aerial surveys and ground observations for efficient decision support systems	

Figure 2. Disaster types, their impact on technology, and system classification.

- type C: meteorological (tropical storm, hurricane, sandstorm, heavy rainfall).

Note that type A disasters render the existing WSN infrastructure for monitoring nonoperational. The assessment and response and recovery phases are performed mainly using UAVs. Type B disasters partially impact the existing WSN infrastructure. In this case, the role of UAVs is twofold: to reconnect the operational parts of WSN and to perform other dedicated tasks. Type C disasters mainly focus on meteorological events, because the UAV can't operate reliably during the assessment phase and has limited operational use in the disaster response and recovery phase due to unstable weather conditions. In this case, the WSN must play a dominant role, with partial support made available through UAVs.

Stage 1: Disaster Preparedness

The preparedness phase doesn't have a predefined duration and could start several years before the anticipated disaster event, culminating with its actual occurrence. For all three disaster types, the WSN plays the lead role, receiving limited support from the UAV. Figure 3 illustrates a case study for flood and landslide monitoring.

In the example scenario, multiple deployed sensors collect physical information—the water level at the monitored bank and vibration/displacement on the mountain side—and forward it to a centralized location, where the information is logged. Here, the simplest option is to use commercial, off-the-shelf cellular modem technology in the sensors, although this increases the weight and cost of the sensors. Simone Frigerio and his colleagues presented a deployment scenario of landslide monitoring in the Italian Alps,[10] where the WSN integrated different sensors to monitor displacements caused by landslides and trigger an alarm in the case of debris flow.

Aerial surveillance via UAVs has limited use in such types of disasters, which require ground-based measurements, because the operational time of the UAVs might not be sufficient to capture the different trends in the natural

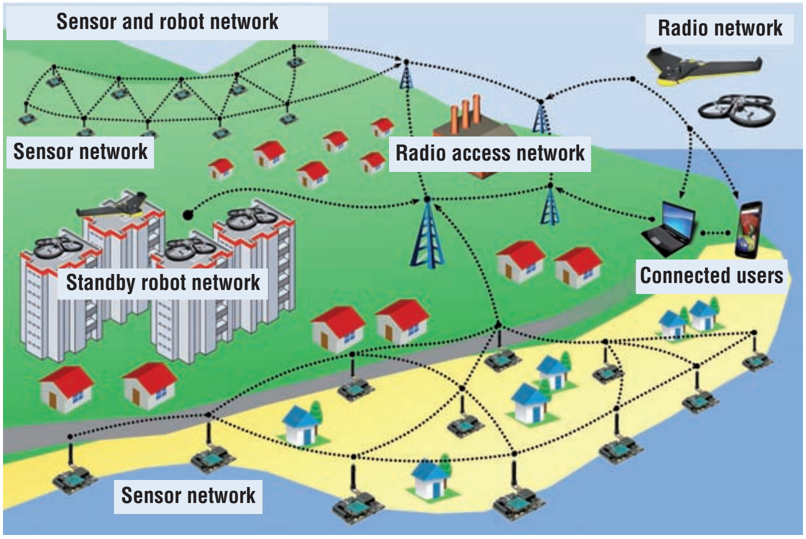


Figure 3. An example mixed-WSN-UAV deployment scenario for disaster preparedness for flood and landslide monitoring. Multiple sensors collect physical information—the water level at the monitored bank and vibration/displacement on the mountainside—and forward it to a centralized location.

parameters being sensed. Instead of sensing, UAVs can play a role by assuming the load of data delivery from the resource-constrained sensors. For example, as shown with the "standby robot network" in Figure 3, stand-by UAVs can be called into active operational service to perform the function of so-called *data mules*.

Our recommendation for this stage is to optimize WSN data acquisition and data analysis to assess the probability of future disaster occurrences, using UAVs as data mules (see Table 2).

Stage 2: Disaster Assessment

This stage occurs when a disaster is in progress, rendering parts of the topographical region unusable for vehicular traffic or human habitation. The focus of the wireless network shifts from monitoring to providing an accurate assessment of the situation. The main task here is surveying the land area for available resources and relaying this data back to the control center, all in real time.

For type A disasters, the UAVs must form an independent network, without support from the ground sensors. When the task assignment is completely centralized, it's possible to partition the physical space into known regions and assign one or more UAVs per region.

When the task assignment is decentralized, the UAVs must first establish an aerial mesh that allows a fully connected network through local coordination (see Figure 4). Multiple UAV stations, strategically deployed over a wide geographical area, can guarantee that at least some parts of the UAV infrastructure are operational, even after the disaster has occurred. Recent works, such as that by Marco Di Felice and his colleagues,[11] rely on using attraction and repulsion spring forces in defining actions of UAVs, with separate air-to-air springs (to form the aerial mesh), air-to-ground springs (to connect the users), and air-to-frontier springs (to allow for the exploration of new spatial locations).

Consequently, for type A disasters, we recommend using heterogeneous UAV networks comprising fixed-wing UAVs to scan the area and identify important points to be covered and surveyed by rotary-wing UAVs.

In the case of type B disasters, the WSN infrastructure is partially operational, so it might still be used in conjunction with the deployed UAV network, which can serve as bridging nodes and sustain the overall WSN topology. Sensor-actor network architectures, which have been studied extensively elsewhere,[12] can be adopted in this scenario. Mobile actors—UAVs here—might move closer to regions of network partitions caused by loss of multiple sensors and act as forwarding relays for the WSN. Although type B disasters bring about interesting joint roles of UAVs and sensors, there are additional considerations. For example, the UAV can serve as the relay node to bridge the network partition only for a short duration, so the comparatively long-lived WSN must buffer and distribute packets along the end-to-end chain.

Gurkan Tuna, V. Cagri Gungor, and Kayhan Gulez have presented an interesting network paradigm in the context of mobile robots that can also be considered for UAVs.[13] In their work, because the WSN is still operational and able to route packets to the remote sink, the mobile units perform more of the exploratory tasks but then leverage the WSN as the data-forwarding backhaul.

For type B disasters, we recommend taking advantage of the existing WSN infrastructure and dedicating a part of the UAV network for WSN infrastructure reconnection. The WSN can not only acquire environmental data but also help reconnect disjoint parts of the UAV network.

Given the particular nature of type C disasters, there are instances of violent turbulence, strong winds, and other weather-related artifacts that don't allow safe airborne operation of the UAVs during the assessment phase. When situational awareness must be delegated to the WSN alone, a viable approach seems to be to use deployments such as *DistressNet*, an ad-hoc wireless architecture that supports disaster response with distributed collaborative sensing, topology-aware routing using a multi-

TABLE 2
Recommendations for WSN and UAV use during a disaster. The recommendation for Stage 1 is the same regardless of the type of disaster, but recommendations differ by type for Stages 2 and 3.

Disaster type	Disaster stage: 1. Preparedness	2. Assessment	3. Response and recovery
Type A (geophysical or hydrological)	Optimize WSN data acquisition and data analysis to assess the probability of future disaster occurrences, using UAVs as data mules.	Use heterogeneous UAV networks comprising fixed-wing UAVs to scan the area and identify important points to be covered and surveyed by rotary-wing UAVs.	Use different camera types and specialized sensors and actuators mounted on UAVs, dedicated for rescue missions and supply delivery.
Type B (climatological, hydrological, or human-induced)	*Same as above*	Exploit the existing WSN infrastructure and dedicate a part of the UAV network for WSN infrastructure reconnection. The WSN can acquire environmental data and help reconnect disjointed parts of the UAV network.	Maximize the data provided by the WSN to improve the efficiency of the search and rescue missions executed by UAVs.
Type C (meteorological)	*Same as above*	Focus on the data provided by the WSN and other available information sources (such as social networks).	Use the fully functional WSN to reconnect the impaired UAV networks.

channel protocol, and accurate resource localization.[14] DistressNet is implemented on a set of available sensors; mobile and static gateways; and a set of servers providing network services, data analysis, and decision support.

Our recommendation for type C disasters is to focus on the data provided by the WSN and other available information sources (such as social networks).

Stage 3: Disaster Response and Recovery

The UAV network will play a critical task in this phase by first establishing short-distance cellular connectivity with the affected users and then transferring data to the backbone cellular infrastructure via a relay network (Figure 4). The network can also give feedback to users about safe areas and evacuation routes based on the information gathered following the disaster assessment phase.

For a type A disaster, the aerial connection plane involves creating a multihop relay network of UAVs that extends from isolated blocks of users to the nearest functional RAN. This results in a multiobjective optimization problem of maintaining the intermediate forwarding capability and the last-mile connectivity to the users.[11]

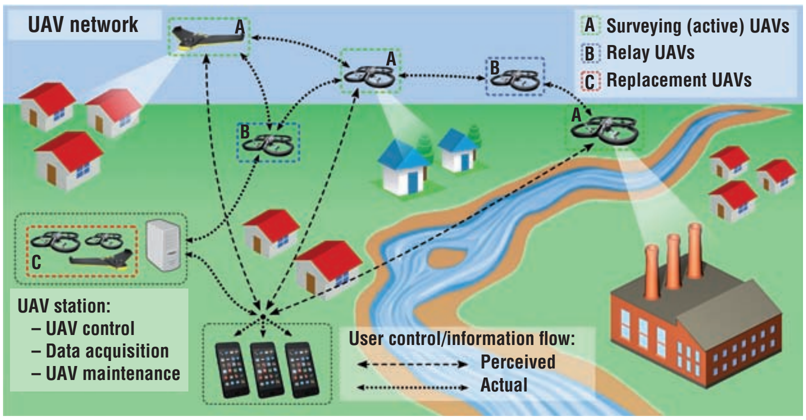


Figure 4. Network architecture for aerial connectivity plane. Multiple UAV stations, strategically deployed over a wide geographical area, can guarantee that at least some parts of the UAV infrastructure are operational even after the disaster has occurred.

An interesting new paradigm will emerge at the crossroads of wireless software-defined networking (WSDN) and the need to establish the aerial connectivity plane, especially in large-scale disasters with thousands of affected users. This scenario can be envisaged as a set of open-flow switches embedded inside the UAVs, whose routing functions can be dynamically altered through commands issued by a remote controller.[15]

Our recommendation for type A disasters is to focus on the use of different camera types and specialized sensors and actuators mounted on UAVs dedicated to rescue missions and supply delivery.

For a type B disaster, when the supporting WSN is fully operational, it can be used to assist the UAV operation by offloading some of the non-time-critical tasks. For example, when two major earthquakes occurred in the Emilia-Romagna region in Northern Italy, UAV operators were overwhelmed by information-retrieval tasks.[16] Here, closely monitoring the information that flows back and forth from the disaster area to the end controller caused human errors in the operation of the UAV, and negatively impacted its performance in the rescue mission.

An existing WSN can also contribute to the on-the-fly establishment of multihop wireless access networks. The architecture Quang Tran Minh and his colleagues have proposed[17] extends Internet connectivity from surviving access points to disaster victims through individual mobile devices. Similar concepts can be extended for the mixed WSN-UAV architecture, where UAVs form the virtual access points and the WSN connects to this UAV network.

Our recommendation for a type B disaster is to maximize the data provided by the WSN to improve the efficiency of the SAR missions executed by UAVs.

In a type C scenario, UAVs are limited in their ability to gather useful information from the disaster site, but they can operate from the periphery. Assuming the disaster involves major destruction to the communications infrastructure, where cellular towers or fixed base stations are rendered ineffective, the only solution is for sensors to forward their data using low power, forming multihop relay chains to the edge of the affected region. The advantage of using UAVs is that the pick-up point at this edge can be dynamically decided based on the surviving elements of the initial architecture. The use of mobile UAV stations proposed in our work can ensure the rapid UAV deployment and prompt UAV network setup, thus lowering the response time and increasing the disaster recovery rate.

Our recommendation is to use the fully functional WSN to reconnect the impaired UAV networks.

Open Issues and Challenges

Involving UAVs in disaster management has several networking-related research challenges. Among the numerous issues that the use of UAVs implies, we have chosen the ones with the most important impact on communication.

Type A and B Disasters

Focusing on type A and B disasters, the following are the issues and challenges that need to be addressed.

Creating and maintaining the information relay network. The relaying network formed by the UAVs is completely aerial and must have a high level of resilience toward link outages owing to motion-related changes or energy-level changes among the UAVs. Addressing this issue requires a two-stage process: an initial round of centralized determination of optimal relay points (which we call *anchors*) that connect the disaster region to the nearest RAN, followed by a round of decentralized correction during deployment.

Supporting in-network data fusion. The video/images collected by the UAVs present an overview of the situation. However, affected humans might also use various social media or forward text messages and images via the UAV relay network. Such activity offers fine-grained on-the-ground information that can be fused at the control center with the high-definition UAV feeds. Existing source/channel coding from the domain of multimedia sensor networks isn't sufficient, because existing coding considers a static network topology with varying channel conditions.[18]

Addressing handover issues. Unlike handoff in cellular systems, the handover among UAVs—such as during recharging events—is considerably more involved. A handover involves replicating the exact operational state in the incoming UAV—including forwarding tables, packets in the buffer, and data fusion rules—which escalates the messaging between the UAVs. The handover process can begin early, during the approach time of the UAV toward the designated location, although this involves higher transmission power and increased impact on the 3D propagation environment. On the other end, there is a tradeoff between the advantage of aerial stability during handover-related messaging with low transmission power and the correspondingly lengthy duration for completing the entire handover process.

Type C Disaster: Strengthening Hardware

With a type C disaster, UAV physical constraints compromise communication. In the context of disaster management, one of the most important constraints imposed on the use of UAV networks is their resistance to weather conditions. In effect, it's reasonable to assume that the appearance of a natural disaster is followed by other natural calamities that would disable the use of UAVs. Therefore, it's important to focus on the development of specialized hardware suitable for disaster environments, as well as control algorithms that could improve the collective behavior and agility of a UAV network.

General Issues

Issues that need to be tackled regardless of the disaster type can be summed up in the following.

Automating network maintenance and UAV charging. Battery-powered UAVs might need to intermittently dissociate from the relay network for charging. Duty-cycling these UAVs—that is, selecting their alternating operational and charging durations—requires careful optimization formulations to maintain relay-path connectivity, provide an adequate level of service to users, and minimize the downtime of each UAV.

Interesting problems exist in this space. The first is performing optimal handoffs between the roles of surveying, last-mile communication with users, and data relaying. Another is choosing the charging duration—that is, making tradeoff decisions regarding whether charging instants should be proactive, even if their battery isn't completely depleted. The final problem deals with optimizing the number of hops by building accurate 3D channel models for various weather conditions and land topologies.

Increasing UAV network security and robustness. To provide robust UAV network control and information acquisition, emphasis must be placed on communication security. Malicious attacks are closely related to UAV network operation, so robust communication protocols play a critical role.

Handling UAV failures. To ensure the fail-safe operation of the overall system, a human operator must be present to supervise the UAV station. This human supervisor can reset or stop the UAVs by engaging a kill-switch or by manually overriding the UAV control. Once the system proves feasible in practice, more advanced automated failure-handling procedures should be envisioned and implemented.

Ensuring privacy and trust. Using UAVs to gather multimedia information about the people affected by a natural disaster can raise important questions of information privacy and trust. Indeed, video footage recorded by a UAV during the disaster response can contain sensitive frames (such as dead or wounded people) that should be automatically censored, especially if the footage is used by the media.

Realizing the next-generation architectures proposed here will require creating new network paradigms, such as aerial WSDNs, and enhancing established theoretical frameworks, such as wireless sensor-actor networks. Furthermore, we need to design reliable and effective networks of UAVs to minimize loss of life and property. We hope our new perspective for classifying disasters and developing suitable network architectures is just the start when it comes to UAVs for disaster management, as disaster victims will be increasingly looking to the sky for relief.

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REFERENCES

1. "Loss Events Worldwide 1980–2014," map, NatCatSERVICE, 2015; www.munichre.com/site/touch-naturalhazards/get/documents_E2080665585/mr/assetpool.shared/Documents/5_Touch/_NatCatService/Focus_analyses/1980-2014-Loss-events-worldwide.pdf.
2. S.F. Ochoa and R. Santos, "Human-Centric Wireless Sensor Networks to Improve Information Availability During Urban Search and Rescue Activities," *Information Fusion*, Mar. 2015, pp. 71–84.
3. D. Chen et al., "Natural Disaster Monitoring with Wireless Sensor Networks: A Case Study of Data-Intensive Applications Upon Low-Cost Scalable Systems," *Mobile Networks and Applications*, vol. 18, no. 5, 2013, pp. 651–663.
4. *Drones for Disaster Response and Relief Operations*, American Red Cross, 2015; www.issuelab.org/resources/21683/21683.pdf.
5. D. Camara, "Cavalry to the Rescue: Drones Fleet to Help Rescuers Operations over Disasters Scenarios," *Proc. 2014 IEEE Conf. Antenna Measurements & Applications* (CAMA), 2014, pp. 16–19.

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6. M. Erdelj and E. Natalizio, "UAV-Assisted Disaster Management: Applications and Open Issues," *Proc. 2015 Int'l Conf. Computing, Networking and Communications* (ICNC), 2016, pp. 1–5.
7. A. Gaszczak, T.P. Breckon, and J. Han, "Real-Time People and Vehicle Detection from UAV Imagery," *Proc. SPIE*, 2011; doi: 10.1117/12.876663.
8. K. Fujii, K. Higuchi, and J. Rekimoto, "Endless Flyer: A Continuous Flying Drone with Automatic Battery Replacement," *Proc. IEEE Conf. Ubiquitous Intelligence and Computing and Autonomic and Trusted Computing* (UIC/ATC), 2013, pp. 216–223.
9. E. Montijano et al., "Vision-Based Distributed Formation Control without an External Positioning System," *IEEE Trans. Robotics*, vol. 32, no. 2, 2016, pp. 339–351.
10. S. Frigerio et al., "A Web-based Platform for Automatic and Continuous Landslide Monitoring: The Rotolon (Eastern Italian Alps) Case Study," *Computers and Geosciences*, vol. 63, 2014, pp. 96–105.
11. M. Di Felice et al., "Self-Organizing Aerial Mesh Networks for Emergency Communication," *IEEE Symp. Personal, Indoor, and Mobile Radio Communication* (PIMRC), 2014; doi: 10.1109/PIMRC.2014.7136429.
12. T. Melodia et al., "Communication and Coordination in Wireless Sensor and Actor Networks" *IEEE Trans. Mobile Computing*, vol. 6, no. 10, 2007, pp. 1116–1129.
13. G. Tuna, V.C. Gungor, and K. Gulez, "An Autonomous Wireless Sensor Network Deployment System Using Mobile Robots for Human Existence Detection in Case of Disasters," *Ad Hoc Networks*, Feb. 2014, pp. 54–68.
14. S. George et al., "DistressNet: A Wireless Ad-Hoc and Sensor Network Architecture for Situation Management in Disaster Response," *IEEE Communications Magazine*, vol. 48, no. 3, 2010, pp. 128–136.
15. I.F. Akyildiz et al., "SoftAir: A Software Defined Networking Architecture for 5G Wireless Systems," *Computer Networks*, 2015, pp. 1–18; doi: http://dx.doi.org/10.1016/j.comnet.2015.05.007.
16. G.-J. Kruijff et al., "Rescue Robots at Earthquake-Hit Mirandola, Italy: A Field Report," *Proc. 2012 IEEE Symp. Safety, Security, and Rescue Robotics* (SSRR), 2012; doi: 10.1109/SSRR.2012.6523866.
17. Q.T. Minh et al., "On-the-Fly Establishment of Multihop Wireless Access Networks for Disaster Recovery," *IEEE Comm. Magazine*, vol. 52, no. 10, 2014, pp. 60–66.
18. T. Banerjee, K.R. Chowdhury, and D.P. Agrawal, "Using Polynomial Regression for Data Representation in Wireless Sensor Networks," *Wiley Int'l J. Communication Systems*, vol. 20, no. 7, 2007, pp. 829–856.