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Improving Resilience Using Drones for Effective Monitoring after Disruptive Events

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ABSTRACT

We observe a world of increasing anxiety due to natural and man-made disasters, pandemics, and military conflicts. Such disruptive events lead to decreased infrastructure and personnel availability; still, infrastructure and personnel are essential for keeping society running, and for addressing the effects of disruptions. We argue that drone technology could provide monitoring/logistics services that can help in addressing such needs. This paper focuses on the monitoring function which can provide situational awareness to decision makers after such a crisis. Drones are less dependent on nearby area infrastructure and can observe affected regions from above. Those are key advantages compared to other solutions. Still, drones are dependent on communication services and ground operators. Therefore, we need drone solutions that are less dependent on the availability of local infrastructure and people. Several conceptual solutions to reach this independence, based on recent developments in drone technology, are explicitly discussed in the current paper and confronted with the requirements and boundary conditions posed by disruptive events. Validating such solutions in real emergency situations is left for future work.

KEYWORDS

drone technology; monitoring; disruptive events; resilience

1 Introduction

We observe a world of increasing anxiety due to disasters, pandemics, military conflicts, and so on [1,2,3]. Such crises are often labelled `disruptive events` for which we aim at novel solutions to reduce disruption effects and increase resilience [4]. Unlike normal variability such as seasonal effects in weather that can be predicted relatively well, *disruptive events* often pose a high degree of complexity [5]. That is because our sophisticated societal processes can no longer count on underlying technologies and infrastructure as they are not functioning anymore or are functioning partially, due to the disruption. We argue that in handling disruptions, *autonomous or semi-autonomous technology* can play a big role since regular technology might not be functioning anymore. That is not only because infrastructure can be damaged and unavailable but also because human operators might not be available due to the crisis. Hence, to function during a *disruptive event*, such autonomous technology should be: (i) *context-aware*, in the sense that it supports behavior dependent on the situation at hand [6]; (ii) of *lower dependency on infrastructure*, in the sense that it can survive lost connections due to damaged infrastructure [7]. With these properties, we expect that autonomous entities could still be active also after a *disruptive event*, bringing value in addressing the disruption and possibly reducing its effects.

Inspired by related work [8,9], we argue that `drones` can play such a role because they are autonomous and some drones are context-aware. How can *drones* manage context-awareness? They do this through sensors and software algorithms [10] that, if needed, can receive further support from a ground station. How can *drones* stay autonomous? Firstly, a *drone* usually has a pre-defined mission featuring a main-success scenario. Secondly, some sophisticated *drones* are rich in software that is capable of detecting that values coming in through drone sensors are out-of-bounds with respect to pre-set thresholds. Hence, this would trigger pro-active scenarios to best handle the unexpected situation – that is how *drones* can stay autonomous.

The above recommendations are conceptual and generic. They would have to be implemented in different ways depending on the particular domain of interest, e.g., in one way when considering healthcare-related services and in another way when considering transportation-related services. Hence, in addition to focusing on generic concepts (in the current paper), we will also use a particular application domain as illustration (in future work); in this way, our findings and recommendations are expected to be of bigger practical value. Furthermore, there are crosscutting functions that concern all domains, such as: `monitoring` the situation (capturing data and analyzing this data), planning

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responses, and providing quality-of-service. We argue that findings and recommendations that relate to such crosscutting functions are also of practical value.

This paper addresses *monitoring* by semi-autonomous and context-aware *drones* as a central crosscutting function in crisis management and resilience. We have three reasons for addressing this particular crosscutting function:

- *Monitoring* is of key importance in the process of mitigating the effects of *disruptive events*; as stated by Moßgraber et al. [11], crisis management starts with deploying sensors to monitor the environment, to prepare for decision support and mitigation actions.
- We have opted for considering *drone* technology with it having particular strengths as it concerns *monitoring*; that is mainly because a *drone* is capable of traveling, independent of road infrastructure. In our view, this allows for large areas to be effectively *monitored* from a position in the sky.
- The effects of a *disruptive event* often span multiple domains and *monitoring* is considered crosscutting since sensor feeds are provided for many domains [12].

Hence, the research question we will answer in this paper, focusing on the *monitoring* capabilities of a *drone*, is: **`How can drones contribute to improving resilience after a disruptive event?`** To answer this question, we consider on the one hand *drone* technology and its relevant strengths, namely context-awareness and lower dependency on infrastructure, and on the other hand we consider *disruptive events* and the requirements they pose.

The remaining of this paper is organized as follows: In Section 2 we consider *disruptive events* and their increasing societal impact. In Section 3 we address *drone* technology and in Section 4 we elaborate the two abovementioned *drone* strengths, namely: context-awareness and lower dependency on infrastructure. In Section 5, we explicitly elaborate on the usefulness of *drone* technology in effectively realizing *monitoring* after *disruptive events*. Section 6 is featuring an analytical discussion relevant to all the above and contains the conclusions.

2 Disruptive Events

We consider three types of disruptive events in this paper: disasters, diseases, and conflicts. <u>Disasters</u> may be either caused by nature, e.g. earthquakes, floodings, or hurricanes, or caused by humans, such as power station failures or factory explosions. <u>Diseases</u> can be either local, e.g. caused by contaminated water, or global, such as pandemic virus outbreaks. <u>Conflicts</u>, as considered in the current paper, can relate to terrorism or wars. Referring to statistics [13] and driven by our observations, we argue that these three types of *disruptive events* largely cover the current disruption space around the globe.

Both in *natural disasters* and in *man-made disasters*, we often have physical destruction of key infrastructure and logistics, which in turn substantially blocks essential services in society as well as relief services that relate to the disaster itself. To mitigate this effect, one may opt for counting on less infrastructure dependent solutions. Another issue in disasters is the low availability of personnel. Those affected by the disaster may not be able to show up for work, because they are affected by the disaster themselves (possibly, they have others to take care of and/or the disaster blocks access to their workplace). Business systems may be down: (i) as a result of a lower availability of personnel; (ii) or because of power outages; (iii) or because of disruptions in the communication systems or Internet. It is common that supplies are low during a disaster. For companies and shops, this is due to the affected logistics, business systems, and employees. Hoarding behavior by citizens plays a role as well when the disaster has been predicted. Right after the disaster, there is often a huge lack of information about affected people and their imminent needs. After hurricane *Katrina* made landfall in the USA, it took FEMA rescue workers multiple days to build a full picture of the effects of the disaster and to reach some of the cities that were hardest hit, because roads were impassable and the land was still flooded, but especially because there was no situational awareness [14].

In *large-scale contagious disease outbreaks* such as pandemics, infrastructure is not directly affected (as in disasters) but the effects on personnel, business systems, and logistics can be severe. The health system gets overloaded because the number of people to take care of increases while the number of health professionals showing up for work decreases, as they may also be affected by the disease. Infrastructures and business systems are influenced by large disease outbreaks as well since fewer people show up for work, either because they are ill or because they do not want to run the risk of getting infected. This also has a negative influence on the ability to deliver medication and healthcare supplies to the affected people and regions. In the recent SARS-CoV-2 pandemic, hoarding behavior and empty shelves were also observed as a result of preparations for quarantine and lockdowns. Combined with logistics and business system problems, this can lead to shortages of critical supplies for the community [15]. Communication systems and Internet typically stay up during a large-scale disease, though.

Military conflicts often target intentional destruction of equipment and infrastructure. This does not only hold for wars but also for local military conflicts and terrorist actions. In such situations, one cannot count on key infrastructure anymore. Further, business systems and logistics are heavily influenced, resulting in problematic supply of critical goods such as food, medicines, and relief goods. Finally, what exacerbates the issues even more is that during a military conflict, it is dangerous to travel, so employees might not show up for work [16]. Hence, situational awareness is of key importance during a conflict. This is because information is not freely shared, might be classified, and spreading of misinformation can be part of the conflict strategy.

We can conclude from the above that the main issues during a *disruptive event* are: (i) *low or no infrastructure availability*; (ii) *personnel possibly not showing up for work*; (iii) *low business system availability*; (iv) *low availability of general goods and relief goods in the affected areas*; (v) *logistics issues for getting food, medications* *and relief goods to the right place*, and (vi) *lack of monitoring capabilities to build a full picture of the effects of the disruptive event and the exact needs*. This all clearly shows that autonomous solutions that are not dependent or less dependent on standard infrastructure, and not dependent on human operators, can be of great help for issues (i), (ii) and (iii). We argue that *drones* as a solution have enormous potential to help in addressing issues (iv) and (v). Further, when *drones* are equipped with sensors and can operate autonomously, all issues (i) to (vi) can be tackled, in our view.

This inspired us to combine the requirements for addressing *disruptive events* with relevant strengths of *drone* technology, to aim for maximum resilience after a *disruptive event*. The following section will analyze the state-of-the-art in *drone* technology to assess its potential for that purpose.

3 Drone Technology

Featuring a system of systems, *drone* technology is characterized by autonomous pilotless airborne vehicles, called **drones**, whose navigation is supported by human operators who act from ground stations and supported also by satellite services (or fully autonomous and guided by satellite services only). A *drone* needs a launch-recovery support, such that flight initiations and terminations are adequately facilitated. *Drones' monitoring* and payload carrying capabilities are of high societal relevance, especially for infrastructure-poor areas or areas that are dangerous for humans. Usefully replacing a human, a *drone* can be autonomous, pro-active, context-aware in its behavior in the sky [17,18].

Figure 1 shows a *drone* as part of a larger system taking care of positioning and communication through the satellite layer, and mission preparation and handling through a ground station. The *drone* system itself (in the middle layer) is equipped with propulsion and avionics to be able to fly, with a navigation engine to find its position, payload systems and actuators to carry out its mission, and sensors to provide context-awareness for its own mission as well as for the services it provides in the emergency situation. Various communication channels with the appropriate level of encryption can be used by the *drone* to communicate with satellites and with the ground station. For more information on what is represented on the left side of the figure, interested readers are referred to [19]. Further:

- Even though the bottom layer, featuring the **ground station**, is infrastructure-dependent and would therefore be vulnerable during a *disruptive event*, it is replaceable in the sense that the *drone* can switch between multiple ground stations. Furthermore, the ground station for handling the *drone*'s mission does not necessarily have to be in the area affected by the *disruptive event*. Replaceability and location independence therefore reduce the criticality of this layer in emergency situations.
- A **drone** itself, as presented in the middle layer of Figure 1, is certainly infrastructure-independent in the sense that all systems within the *drone* can work on their own, except for the vital links to the ground station and the satellites.
- Finally, in the top communication and positioning layer, we have mentioned **satellite services** as the default technology to use, since it is a public service that is world-wide available, and usually not affected by local infrastructure outages. If necessary, a *drone* can switch between different communication frequency bands and between the available global positioning technologies. That is why we have labelled the top layer as having a low infrastructure dependency.

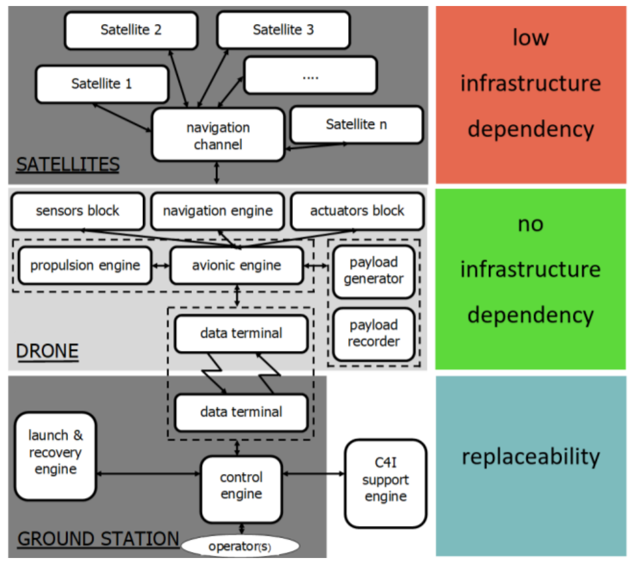

Figure 1: A drone in relation to its environment as a system-of-systems, with the infrastructure dependency depicted on the right-hand side.

In summary, *drones* are considered infrastructure-independent, counting on ground stations that can be replaced and also counting on satellite services that can be utilized through different communications channels. All this makes *drone* technology attractive concerning *disruptive events*; criticality of vulnerable infrastructure is mitigated. It therefore makes sense to use *drones* for *monitoring* activities during/after *disruptive events*, of course in areas where this could work effectively.

4 Context-Awareness and Infrastructure Independence of Drones

As mentioned already, *drones* are capable of effectively managing context-awareness, supported not only by embedded sensors and software algorithms but also by ground/satellite services. In addition to the more technical term "context-awareness" (meaning the capability of a technical entity to sense the situation at hand and adapt its behavior accordingly [20]) we also use in this paper a more general term "situational awareness" (meaning just the ability to adequately establish the "current" situation, without necessarily taking actions accordingly).

In particular: (i) The *drone*'s software is often capable of calculating the point of no return, related to corresponding resource (battery/fuel) monitoring; when approaching this point, the *drone* would start warning the ground station, asking for being either navigated back or given a new landing goal. When no response would be received, the *drone* could pro-actively fly back or continue its mission, choosing a landing spot where it can easily be picked up [21]. (ii) The DAA (Detect And Avoid) technology concerns a safety distance implemented by *drones* with regard to planes in the sky. Even though DAA is quite difficult to apply in crisis situations and it suffers from lack of standardization and scalability potentials, it is the basis for further technological developments, such as the emerging UTM (Unmanned Traffic Management) standards [22,23].

Suppose we have a certain location, such as a city or a district, affected by a *disruptive event*. Then key infrastructure and services at that location may be completely or partially down. Due to the *disruptive event*, the need for certain services might be higher than before the disruption, for example: transportation services, communication services, safety & security services, and healthcare services. The need for other services might stay the same as before the *disruptive event*, for example: food delivery services and postal services. With the disrupted infrastructure and service provision, addressing the normal service needs is often already impossible, let alone the additional service needs. In our view, four recommendations are important here: (i) Reducing dependencies on inoperative components; (ii) By-passing affected infrastructure; (iii) Dealing with missing data; (iv) Re-prioritizing service provision, focusing on just the core activities and delaying less important ones to be addressed later.

As already suggested, the relevant strengths of *drone* technology (grounded in the technical possibilities discussed above in the current section) are useful as it concerns the above recommendations.

Those strengths can be seen in immediate practical applications, beyond *disruptive events*, as illustrated in Figure 2.

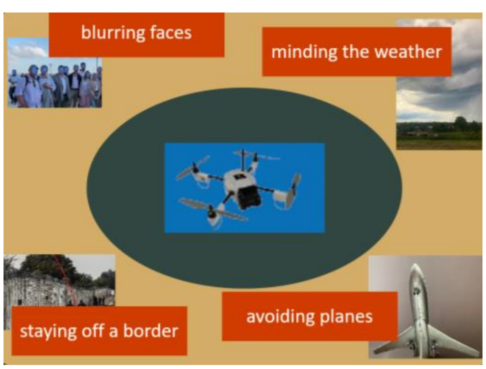

Figure 2: A drone's context-awareness and less infrastructure dependency: a practical perspective.

As the figure suggests: [up-left] A *monitoring drone* can well establish that it is video-recording human faces and it may start "blurring" them, for the sake of PRIVACY protection; [up-right] Upon sensing a storm, a *drone* may take actions to PROTECT ITSELF and its mission; [down-left] A *drone* may find out that it is approaching a state BORDER and fly back; [down-right] A *drone* may be pro-active in avoiding disturbance with regard to a NEARBY PLANE.

It is not only that we consider this **CONTEXT-AWARENESS**, because it is about a *drone*'s sensing its situation and adapting its behavior accordingly, but it is also that in this the *drone* stays **INFRASTRUCTURE-INDEPENDENT**, because it utilizes satellite services through different channels and flexibly re-arranges the ground station support, as discussed already.

Hence, similar actions may be taken in different situations after a *disruptive event* has occurred. In the following section, we will continue the current discussion, narrowing it to *monitoring*.

5 Drones for Monitoring

In general, *monitoring* is about gathering information and either directly transmit this information for further analysis, or locally process the information and possibly trigger an alarm when incoming values reach a pre-defined threshold [24]. Even though such a function can be realized in different ways, we limit ourselves to only considering automated technical monitoring by a *drone*. We argue that *drone monitoring* is mainly about the remote provisioning of situational awareness, to serve decision making. In our view, this is of high relevance as it concerns *disruptive events* – see the discussions in the previous sections of the current paper. For the sake of brevity, we do not cover the data perspective: what data sources are used, how pieces of data are combined, how to guarantee quality-of-data, and so on. Instead, we focus on how *drones* can be useful in gathering the data itself, especially after a *disruptive event* has taken place. We are also interested in the ways such missions can be initiated as well as in the reliability of *drone* technology for *monitoring* activities. For the *drone* to work autonomously, we certainly need assurance that all terrain and environmental information is up to date and integrated into the relevant information management systems, at least until the date before the *disruptive event* happened. Of course, a *disruptive event* such as flooding, a volcanic eruption, or an earthquake, can severely transform the environment. We need this basis input to properly establish situational awareness while managing the effects of the *disruptive event*. Because of the destruction as the result of (many) *disruptive events*, we also need adequate post-damage assessment [8]. Here we observe relevant strengths of *drone* technology, which are four-fold: (i) **safety** – because *drones* allow for *pilotless missions*, no humans have to be exposed to dangerous situations that exist after the *disruptive event*; (ii) **flexibility** – the variety of available flight platforms, sizes and characteristics provides a high degree of flexibility that makes *drone* technology effective in successfully tackling *disruptive-events*-related tasks of different kinds; (iii) **cost-efficiency** – for obvious reasons, *drones* offer a significant cost reduction compared to manned data gathering technologies, such as all-terrain vehicles, helicopters or regular surveillance planes;

(iv) **ease of deployment** – the capability of *drone* technology to be rapidly deployed independently of affected infrastructure, by means of catapults and vertical take-off, loaded with the necessary sensors and combined with terrain and GIS data before the event, helps the operators obtain situational awareness and learn which infrastructure is at the greatest risk.

Multi-sensory *drone* aerial *monitoring* (characterized by a multi-view overlapping imagery and video footage) is quite different from technologies counting on observational satellites, where the technologies are sensitive to weather conditions and clouds. Even though *drones* themselves benefit from satellite services for communications, their sensor facilitation is considered essential [26] because they "bring the sensor to the spot" – there cannot be a better and more reliable solution. Hence, the data obtained by multi-sensory *drone* aerial *monitoring* is real-time data and payload sensors data can be directly coupled with the autopilot to process actual multi-layer maps of the area. This is claimed to be giving on-site pictures and understanding of the situation, allowing for better decision making, for the benefit of those who need help after a *disruptive event*.

Hence, right after a *disruptive event* has struck, it is considered helpful using *drones* and their capabilities for search & rescue missions, for the sake of saving as many lives as possible. The next natural step is to use the data gathered during these initial flights to build a comprehensive picture of the situation so that the efforts can be focused on rebuilding the most damaged areas. The best-case scenario would be to layer the newly gathered data on top of the pre-incident GIS data. By doing so, the affected areas can be highlighted, easing the decision making towards resource prioritizations [25].

6 Discussion and Conclusions

Disruptive events have serious effects on society and wellbeing. Even though we aim at avoiding *disruptive events*, things are often beyond our control and *disruptive events* such as disasters, diseases, and conflicts just happen. This highlights the importance of the activities during a *disruptive event* and the activities after a *disruptive event*, such that maximum mitigation is achieved. In the current paper, we have mainly focused on the latter, considering the importance of *monitoring* activities after a *disruptive event* has occurred. In particular, we have studied relevant strengths of *drone* technology, relating them to requirements stemming from the nature of a *disruptive event*.

Those strengths are three-fold:

- *Drones* are pilotless and are therefore capable of realizing tasks in areas that may be risky for humans.
- *Drones* are capable of applying context-awareness during their missions, facilitated by sensors & data processing algorithms, distant support from the ground, and satellite services – this helps drones assess the situation at hand and, if needed, update their behavior accordingly.
- *Drone* technology is much less dependent on changed and possibly damaged infrastructure, compared to other technologies because: (i) a *drone* itself is autonomous; (ii) the ground station supporting the *drone* is not necessarily in close proximity to the *drone* and also, if needed, the *drone* may "subscribe" to another station; (iii) the satellite services, used by a *drone*, can be utilized through different channels.

We have studied these strengths of *drone* technology and justified their relevance to the requirements concerning the post-*disruptive-events monitoring*. Still, we have stayed agnostic of the exact application area and the type of *disruptive event* for which *drone* technology could be used. The validation of the added value of those strengths in actual or simulated post-disruption situations is left for future research.

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