Enhancing Disaster Response for Hazardous Materials Using Emerging Technologies: The Role of AI and a Research Agenda

Jaziar Radianti[1], Ioannis Dokas[2](✉), Kees Boersma[3], Nadia Saad Noori[4], Nabil Belbachir[4], and Stefan Stieglitz[5]

[1] University of Agder, Kristiansand, Norway
jaziar.radianti@uia.no
[2] Demokritus University of Thrace, Xanthi, Greece
idokas@civil.duth.gr
[3] Vrije University, Amsterdam, The Netherlands
f.k.boersma@vu.nl
[4] NORCE Research, Oslo, Norway
{nano,nabe}@norceresearch.no
[5] University of Duisburg Essen, Duisburg, Germany
stefan.stieglitz@uni-due.de

Abstract. Despite all efforts like the introduction of new training methods and personal protective equipment, the need to reduce the number of First Responders (FRs) fatalities and injuries remains. Reports show that advances in technology have not yet resulted in protecting FRs from injuries, health impacts, and odorless toxic gases effectively. Currently, there are emerging technologies that can be exploited and applied in emergency management settings to improve FRs protection. The aim of this paper is threefold: First, to conduct scenario analysis and situations that currently threat the first responders. Second, to conduct gap analysis concerning the new technology needs in relations to the proposed scenarios. Third, to propose a research agenda and to discuss the role of Artificial Intelligence within it.

Keywords: Hazardous materials · Emerging technologies · Emergency management · First responders

1 Introduction

First Responders (FRs) have one of the deadliest jobs in the world since they operate very close to unpredicted dangers, such as a sudden gas explosion, release of deadly chemicals, building collapse and heart attacks. As a result, several FRs are injured or lose their lives in action due to the lack of awareness of unpredicted risks, of hazardous materials and material exposure. FR fatalities compose more than half of the total fatalities of the incident in some cases. For example, the 2007 forest fires in Artemida, Greece resulted in 26 fatalities 3 of which were firefighters (11%), the 2013 West Fertilizer Company incident in Texas, USA resulted in 15 victims where the FR victims accounted for 53% fatalities. In the 2015 chemical blast in Tianjin-China, there were

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173 fatalities, where 104 of them or 60% were FRs [1], Likewise, in the event of a high-rise building fire in Tehran 2017, 16 out of 22 fatalities or 72% were FRs. This reveals how far FRs are exposed to deadly risks in response operations.

Situational Awareness (SA) also has a significant impact on the incident management and coordination, where it is critical for "all knowledge that is accessible and can be integrated into a coherent picture, when required, to assess and cope with a situation" [2]. Today, the integration of Information and Communication Technology (ICT) and mobile technologies in emergency management is reshaping communications and information exchange between the command and control centres (C2C) and FRs on the incident site. Also, ICT has provided several opportunities for advanced-sensing, computing and communicating through smartphones, wearable-portable devices, robotics and unmanned aerial vehicles (UAVs).

However, reports show that advances in technology have not yet resulted in protecting FRs from injuries, health impacts, and odorless toxic gases effectively [3]. For example, a recent study reveals that the mean number of firefighters' fatalities in Sweden has increased from 2000 to 2016 [4]. Indeed, the International Forum to Advance First Responder Innovation's [5] has published a list of four FR capability gaps, namely the ability to: (a) Know the location of responders and their proximity to risks and hazards in real time. (b) Detect, monitor and analyze passive and active threats and hazards at incident scenes in real time. (c) Rapidly identify hazardous agents and contaminants. (d) Incorporate information from multiple and nontraditional sources (e.g., crowdsourcing and social media) into incident command.

Briefly, we see some capability gaps concerning the identification of hazardous agents and detecting, monitoring and analyzing passive and active hazard. For example, FR personnel often need to be close enough to the sources before realizing the presence of a passive and active hazard. In short, there is a strong need to innovate with new technologies for first responders to address their capability gaps. Sometimes, the issues not only about emerging technologies but also methods how to use existing technologies efficiently so that FRs are protected. Here, often a common operational picture and situational awareness play a role, and technologies can enhance these situations.

The aim of this paper is threefold: First, to conduct scenario analysis and situations that may put FRs in different types of threats. Second, to conduct gap analysis concerning the new technology needs and specifications in relation to the proposed scenarios. Third, to propose a research agenda and to discuss the role of Artificial Intelligence (AI).

This paper is organized into five sections. Section 2 describes the theoretical background on the importance of common operational picture and situational awareness. Section 3 describes three scenarios where the hazardous materials can come into the picture and be unexpected extra disasters. Section 4 elaborate examples of potentially relevant, emerging technologies that can be scrutinized further for protecting the FRs. Section 5 is a proposed Research Agenda. Section 6 is the concluding remark.

2 Theoretical Background

To understand the risks and threats exposed to the first responders, literature in emergency management has emphasized the importance of the three following perspectives. First, Common Operational Picture (COP). *Second*, Shared Situation Awareness (SA), and *third*, Collective Sensemaking and Advanced Decision Making.

The COP is a way to 'achieve a sufficient level of shared information among the different organizations and jurisdictions participating in disaster operations at different locations, so all actors readily understand the constraints on each and the possible combinations of collaboration and support among them under a given set of conditions' [6]. SA is a precondition of any COP. It is the perception of environmental elements and events concerning time or space, the comprehension of their meaning, and the projection of their status after some variable has changed, such as time, or some other variable, such as a predetermined event. SA involves being aware of what is happening at times of uncertainty to understand how information, events, and one's actions will impact goals and objectives, both immediately and in the near future [7]. One with an adept sense of situation awareness generally has a high degree of knowledge with respect to inputs and outputs of a system, an innate "feel" for situations, people, and events that play out because of variables the subject can control. Lacking or inadequate situation awareness among responders with different backgrounds (i.e., shared situation awareness) has been identified as one of the primary factors in accidents attributed to human error. SA is related to Advanced Decision Making, which is the process followed in processing information to assess situations for making collective decisions and taking collaborative actions. Decision making is part of all management tasks and that it is particularly important for emergency managers as they often need to take decisions quickly on very inadequate information [8, 9]. Collaborative group decision making plays an important part in first response operations. We see collaborative interactions through the construct of heedful interrelating, which refers to interacting with sensitivity to the task at hand while at the same time paying attention to how one's actions affect overall group functioning [10–12]. Advanced decision making is related to the process of collaborative sensemaking.

Collective sensemaking is about building a sufficient level of shared understanding in a sensemaking process in which members of different professional organizations (de/re)construct information influenced by their institutional background to find out what is going on in times of uncertainty [13]. This sensemaking process is based upon the knowledge responders have gained through (1) education, including training/exercises; (2) storytelling; and (3) past experiences [14, 15]. FRs have to constantly make sense of the situation and of the actions of other FRs (collectively) because of the rapidly changing environment [16]. Sensemaking can be understood as a steady process [17] of gaining knowledge through the transformation and integration of new information into cognitive schemata [18], which is particularly essential in crises to understand such unstable situations and to make adequate decisions. Therefore, it aims to reduce and bridge knowledge gaps [19–21] and can be impacted by several social factors like opinions [19, 20] as well as interactions, discussions or information from other individuals [13] to find common ground for decision making.

For the first responder to have/get an adequate overview of the crisis situation and the actions of (other) responding organizations, they need to create a common operational picture (COP). Information/data is needed to come to a coherent but dynamic COP. In practice (in line with the literature) this happens only if they have sufficient situational awareness (SA). SA is based on the collecting and sharing of information. SA is not static (as the crisis situation continuously evolves and more responding organizations become active), nor univocal or unambiguous. On the contrary, SA is ambiguous and multivocal, because responding organizations will give (different) meanings to the crisis situation, to the information and to what is needed to respond to the crisis (i.e., decision making). A concept of collective sensemaking approach to understand and unravel the multivocality and ambiguity, to understand how various responders with their specific professional norms and routines interpret the situation, and finally how they enact the responding practices in such a way (that is, collectively) that the joint effort and operations become more efficient.

In the next section, we provide examples of the most frequent man-made and natural disasters involving hazardous substance. The aim is to illustrate that people can easily lose their situational awareness in such events and different understanding of the situations. Moreover, people often don't know that hazardous material leaked into, e.g., burning building, or even into water systems, where the danger is not only involving the first responders alone but also society in general.

3 Scenario Analysis

Disastrous events concerning hazardous materials can occur in different settings. Three scenarios presented below can serve as an illustration, why new technologies are required. We select three examples of scenarios, i.e., industrial accidents, natural hazard, and terrorist attack.

3.1 Industrial Accidents

Industrial accidents involving the release of dangerous substances, explosions or fire frequently occur in Europe, causing severe adverse effects to people, properties and the environment. Major toxic spills from mining activities in Europe occurred such as Baia Mare, Romania (2000), Aude/Malvesi, France (2004), Kolontár, Hungary (2010) – all due to dam failures, and in Borsa, Romania (2005) – due to the accidental release of 300 m^3 of cyanide solution into a river. Likewise, leakage of pipelines in a process plant, followed by fire and explosion happened such as in Priolo Gargallo, Italy (2006), explosion and fire rupture of pipeline in Dormagen Germany (2008).

One of the threats to the FRs when implementing their duties in industrial accidents are these unknown hazardous materials (hazmat). Hazmat is chemical substances that if released or misused can pose a threat to property, the environment or health. Such chemicals are prevalent in many industries and products which often use materials that may be explosive, flammable, corrosive, poisonous, radioactive, or otherwise toxic or dangerous. Depending on the nature of the hazardous material, the result of a release or spill can include death, serious injury, long-lasting health effects, or physical damages

of buildings and environment [22]. It can cause fatalities and injuries of workers, damage to property and infrastructure on site and in the surrounding area, critical service disruptions, contamination.

3.2 Natural Hazard Event

Flooding is the primary risk faced by many countries. Flood events frequently occur across the multiple countries in the form of a river, flash and water surface floods, and coastal flooding. Flooding understood in broad terms to include floods from rivers, mountain torrents, and floods from the sea in coastal areas, but exclude floods from sewage systems, as defined under the European Floods Directive. Several major flood events have occurred.

For instance, in 2017 in Greece, according to the official data from the Hellenic Civil Protection Command Center 70 floods events were being reported that needed the deployment of First Responders. Other major floods events occurred in the Former Yugoslav Republic of Macedonia and Albania (2015, 2016), Serbia and Croatia (2014), Slovenia (2014), Sardinia and Slovakia (2013) and Austria, Germany and Czech Republic (2013), Norway (2017). Floods often lead into cascading effects such as disruption of critical services and infrastructure, the outbreak of epidemic or epizootic events and damage to industrial facilities causing the release of chemical, biological, radiological and nuclear substance [23].

3.3 Terrorist Attack Event

The fear of terrorism is one of the risks in Europe that deeply rooted in people's mind. Over the past few years, Europe has been struck by several major terrorist attacks such as in Madrid, Spain 2004, in Oslo, Norway, 2011 and in Paris, France, 2015 that created mass panics. According to Europol [24], in 2016 a total of 142 failed, foiled and completed attacks were reported and resulted in 142 victims died, and 379 people were injured in Europe. Among the techniques that are often used in these terrorist attacks are Home-Made Explosives, improvised explosive device attacks on soft targets and the use of suicide person-borne. The use of Chemical, biological, radiological and nuclear, food contaminants and radioactive materials are examples of techniques that are feared.

A serious terrorist attack can have severe impacts including mortality, injury, psychological distress, economic losses, and critical infrastructure damages. From the medical emergency services perspective, there is a risk of a high number of casualties such as wounds, burns or even mass casualties in such an event. One of the usages of social media technology is to help the emergency medical services for faster response by spotting victim location and severity of their injuries. A terrorist attack can also be related to the other types of risks such as epidemics, pandemics, CBRN threat and bioterrorism against facilities with a hazardous substance which again will expose local citizens and environment with substance release that can be poisonous, in addition to the critical infrastructure collapse, damage of property and infrastructure on site and in the surrounding area, critical service disruptions and contamination.

In these three examples of scenarios, the first responders should react quickly, minimizing the loss of lives of the affected people and themselves. If hazardous materials are involved in these examples of disasters, they may be severely exposed to e.g., poisonous gasses, explosive and other dangerous substance. We have high hope that existing and emerging technologies can help the first responders detecting early all potential hazards and have better preparedness in a disaster. The next section describes the example of emerging technologies that potentially are useful for emergency management.

4 Emerging Technologies

Currently, there are emerging technologies that can be exploited and applied to improve the way how FRs can be protected, such as:

- Unmanned Aerial Vehicles (UAV) with various mounted sensors and cameras: currently researchers examined different levels of the autonomy UAV from fully controlled by operators, computer action alternatives, computer narrow down the choice, the computer executes an action upon the operator's approval to fully controlled by computer and ignoring the operators [25].
- Wearable devices and wearable sensors (Wrist-worn, head-mounted and others) that come as existing products and research prototype. For example:
  - Wrist-worn: smartwatches and wrist bands with or without touchscreen display such as Apple iWatch, Samsung Gear, Pebble Time, Fitbit flex existing products and Smart-watch Life-Saver (prototype).
  - Head-mounted devices: smart glasses such as Funiki Ambient glasses, Recon Jet, Microsoft HoloLens (existing products) and Google glass (prototype),
  - Smart jewelry designed a for health-monitoring such as a smart ring (existing product) or other jewelry such as typing ring and gesture detection ring (prototype)
  - Electronic garments, i.e., clothing items that also serve as wearables such as Athos, Spinovo (existing products) or Dooplesleep (prototype)
  - E-Patch, i.e., sensor patches that can adhere to the skin for fitness tracking or haptic applications, sensing and data transmission. For example, health patch, Motorolla e-tattoo or stamp platform (existing products) or duoskin, smart tooth patch (prototype) [26].
- *AR/VR technologies*: Currently, different technologies have been available to support the immersive experience with virtual reality and augmented reality such as head-mounted display Oculus rift and HTC Vive. Also, some AR/VR experience can be obtained by using smartphones such as Google Cardboard and the Galaxy Gear VR headset. In addition, immersive video and 360-degree video add additional VR/AR experience possibilities [27].
- *Robotics:* Nowadays, the technology and application areas have been developed rapidly for industrial purposes, rehabilitation and surgery, search and rescue, self-driving vehicles, assistive technology, home care, manufacturing and so on. Examples of care robots: Lifting, exoskeletons, assistive, companion, talking, emotional,

service [28] Research on swarm robotics have focused on several topics such as Aerial manipulation, counter-swarm pursuit, target search, and tracking, surveillance monitoring and mapping [29]. There are more examples indicating that the robotics is increasingly becoming an attractive research area with usefull new applications.

- *Real-time systems*: Today's robust networks allowed the researcher to put "real-time" as a feature or a selling point of any newly created systems in any area. Countless technologies are offering real-time systems as a part of the delivery.
- *Smartphone* with advanced computing power, connectivity, battery, and storage have changed this device into a handy multi-purpose device that can be used for collecting images, videos, audio, location and other sensor data [30, 31].
- *Surveillance camera* with automatic detections (behavioral and facial recognition, object detections, object tracking and so on). Surveillance camera itself is not new, but how people use and process the videos and images have improved significantly, especially after the advancement of image processing techniques developed in artificial intelligence domain.
- *Super-computers* i.e., high level of performance computers that allow processing very large databases and conduct a big amount of computations, such as iDataPlex, Shaheen II, Hazel Han and Trinity. They have 301,056 cores, 185,088 cores, 196,608 cores and 65,320 cores respectively [32]. Advances such as multi-core processors and GPGPUs (General Purpose Graphics Processing Units) have enabled a powerful machine for personal use. Supercomputers will continuously support the advancements of activities dealing with UAV, AR/VR, robotics and so on as more data have been collected and need huge computing power to deliver results in nearly real time.

These technologies generate new types of massive data. Also, some technologies have been exploited by the public to generate citizen information, especially social media, and the use of various mobile and web app that allows researchers to collect data through crow-sourcing technique. Likewise, various research benefited from current fast development of data analysis techniques, especially artificial intelligence especially machine learning, deep learning, and computer vision.

5 Discussion: Research Agenda and the Role of AI

Despite all efforts like the introduction of new training methods and personal protective equipment, the need to reduce the number of FRs fatalities and injuries, to as much as reasonably possible level, remains. New emerging technologies can be used to minimize this problem. However, these technologies must be analyzed (re)designed, studied, tested in emergency management settings and evaluated, considering FRs protection against multiple and unexpected dangers and to what extent they can truly enhance SA and COP.

Therefore, we plan to conduct research in the following areas:

(1) On-Site Threat Detection (real-time portable platform for hazmat detection and monitoring)
(2) Risk Monitoring and Safe Management of Threats

(3) Threat Prevention (real-time monitoring of personnel's psychological status, big data analytics and dispersion-prediction projection of hazardous substance).

AI technologies have a very important role to play in this research agenda. AI can be utilized to retrieve useful types of data from different sources and to generate useful information. To enhance social media data analytics services to be utilized by FRs to enhance their SA dynamically. Can enable FRs to manage and respond, with useful answers drawn from messy, real-world datasets, to a large number of emergency calls by people that ask specific, targeted questions. AI can also be used to enhance predictive analytics programs and through that to enhance the readiness level of FR teams. Lastly AI can be used for the development of advanced chemical sensors that can identify in real time an unlimited number of chemicals in real-world environments. Such a sensor in a wearable edition can provide real time threat detection to the FRs teams that operate in the field.

6 Concluding Remarks and Future Works

There are some gaps when it comes to the technologies that can protect the FRs from hazardous materials, especially the identification of hazardous agents and detecting, monitoring and analyzing passive and active hazard. We found that there are various new, promising research directions, exploiting new technologies to improve the safety of the FRs. In addition AI technologies can be used in conjunction with other emerging technologies to provide enhanced COP, SA and enhanced threat detection and protect FRs by minimizing their casualties. Our future directions are to pursue and operationalize our research agenda into a set of concrete studies that can contribute to the area of emergency management, safety and risk management.

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