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Review

Future Research on Cyber-Physical Emergency Management Systems

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Abstract: Cyber-physical systems that include human beings and vehicles in a built environment, such as a building or a city, together with sensor networks and decision support systems have attracted much attention. In emergencies, which also include mobile searchers and rescuers, the interactions among civilians and the environment become much more diverse, and the complexity of the emergency response also becomes much greater. This paper surveys current research on sensor-assisted evacuation and rescue systems and discusses the related research issues concerning communication protocols for sensor networks, as well as several other important issues, such as the integrated asynchronous control of large-scale emergency response systems, knowledge discovery for rescue and prototyping platforms. Then, we suggest directions for further research.

Keywords: cyber-physical systems; emergency navigation; pervasive computing; search and rescue systems; wireless sensor networks

1. Introduction and Overall Vision

Cyber-technical systems (CPS) use wireless technologies, sensing and distributed decisions based on ubiquitous computing and networks with potential benefits in very diverse areas of human activity, such as [1] the environment [2], security [3], transport systems [4], emergency management [5], discovery of bombs, mines and unexploded ordnance [6,7] and leisure and tourism [8].

Recent survey articles [9,10] have reviewed research on sensor-aided CPSs that enable intelligent and fast response to emergencies, such as fires, earthquakes or terrorist attacks. The present paper will focus on projecting past and recent research in emergency management systems towards research opportunities.

Real-time monitoring and quick response are inherent requirements for emergency response. During a fire, different types of sensors can cooperate and interact with the evacuees and the environment. Temperature and gas sensors can help monitor the spread of hazards. Rotatable cameras track the spread of the fire and the movement of civilians. Ultrasonic sensors can range the distance to obstacles in the environment and monitor dynamic changes of maps, due to sudden changes in some built structures through destruction and debris. Smart evacuation schemes can help evacuees using the cooperation between first-aid decision nodes, sensors and civilians with mobile devices. Evacuees with mobile devices can follow personalised navigation paths with distributed decisions that mitigate congestion. Those without mobile devices may follow audio or visible LED directions. Grid/cloud-supported computing can gather sensing information and dynamically predict the movement of evacuees and hazards to make the best decisions regarding resource allocation and response. A search may also be conducted with the help of robotic devices, despite their limited autonomy [11].

2. Technically Challenging Areas

Since all of these requirements raise many critical challenges, two types of approaches have motivated considerable research to address issues in communications, information acquirement and dissemination, knowledge discovery, resource allocation and management, heterogeneous system integration and asynchronous control, and we discuss some of these challenges below.

- Communication issues: *many-to-many information flow* [12–23] and *opportunistic connection* [24] are inevitable in emergencies. Considering a fire emergency, to find safe paths, sensing information may need to be conveyed from many sensors to many mobile evacuees. This will obviously be more difficult, since communications may break down and evacuees will move to escape. In addition, query-and-reply communications may also proceed between different groups of people, e.g., first responders, evacuees, members of the press and robots. In these cases, typical communication protocols, such as broadcast, convergecast, unicast, and multicast, may be not able to deal with these diverse communication requirements.
- Information acquirement and dissemination: *cross-domain sensing* [25–27] and *heterogeneous information flow* [28–30] are inherent features in an emergency response system. To guarantee the safety of people, information in different domains must be acquired (e.g., ultrasonic sensors for localizing people, temperature and gas sensors for identifying hazards, camera sensors for counting civilians and life detectors for searching civilians). Moreover, sensors are no longer the only information contributors, and *in situ* interactions between sensors, actuators, people, objects and events will also be involved to disseminate and contribute high-level information. These features will raise a challenge to acquire and disseminate information in an efficient way.
- Knowledge discovery: *partial information* and *dynamic changes* are inherent in an emergency. In such a rough environment, feasible and quick response must rely on data analysis technologies

to extract knowledge from sensing data (e.g., counting, discovery, localization and tracking of civilians) [30–38]. Moreover, dynamic prediction and forecast of environmental changes should be conducted to avoid unnecessary casualties [20,21,39–44].

- Resource allocation and management: *limited resources* make timely response more difficult. Unlike other sensor-aided applications, the needs of intelligent actuation, scheduling and efficient resource allocation will increase in emergency response systems. Intelligent scheduling is needed to select the best action, while scarce resources must be allocated efficiently to perform actions [45–50].
- Heterogeneous system integration and asynchronous control: *multi-domain technologies* will be needed to enhance the capability and diversity of emergency response [26,27,30,38]. Furthermore, *functionality separated* tasks, such as sensing, storage, computation and decision-making, need to be conducted by independent functional units, so as to facilitate the integrated asynchronous control of multiple technologies. To achieve this goal, parallel and virtualisation technologies (e.g., grid or cloud computing) may steer the emergency response systems toward functionality-separated approaches for resource scaling, fault-tolerance and computation speed-up [25]. For instance, in an outdoor city-wide environment, large numbers of civilians may be tracked, and massive sensing information can only be stored and computed rapidly by a powerful resource pool.
- Comparison with military systems: the objective of search and rescue systems is emergency response, but military systems focus on extensive simulations for tactical planning and decision. A search and rescue system usually consists of heterogeneous nodes, while a military system is a collection of mission-oriented sub-systems with resources and capabilities that provide complex functionalities that are far more than the sum of constituent systems. A search and rescue system is usually deployed over a smaller space, while a military system emphasises value-added functionalities that usually leave more time for decision-making and resource deployment, while an emergency system must offer an urgent life-critical response. Search and rescue systems may typically also use more limited communications and sensing than the global assets that military systems typically have, such as satellite communications and wide-band radar sensing.

3. Characteristics of Existing Evacuation Systems

In this section, we will first briefly review the salient characteristics of some proposed evacuation systems. References [13–18,20,21,39,42–44] rely on location information regarding the sensors to compute evacuation paths [51], while the deployment of sensors in work spaces and buildings in [12–17,20,21,25,39,42] enables the movement of evacuees and first responders. Except for [12–16,20,21], most approaches require maps either for computing or navigation purposes. Instead of physically sensed input, as in other work, some simulation studies [40,41] use virtual hazards to simulate emergencies. Also, the dynamic spread and shrinking of hazards is considered in [15,19–21,23,25,39,42]. While in [24,28], opportunistic networks are considered, other papers assume that [24,28,29,43,44] mobile users themselves facilitate sensing and communications. In [24,28,29,40,41,43,44] localization technologies to be used are required. We note that in [24,28,29,43,44] personalized navigation directions can be provided to individuals, and the issue of

congestion is also addressed in some papers [16,17]. Table 1 also summarises and compares proposals that have been made for search and rescue systems. In [30,34] searching victims or tracking their movements is the focus, while in [35–37], attention is payed to tracking rescuers (or firefighters) to guarantee their safety. Based on the presence of victims, in [38], the search and rescue space is reduced, and in [32,33], a communication backbone is formed using robotics. The work in [26,27] uses robots to search and guide victims, and in [31], the number of civilians in an emergency is assessed. Finally, the following papers, [45–50], concentrate on the optimization of search and rescue cost.

Table 1. A comparison of search and rescue systems.

functionalities	reference
Localization/tracking of civilians	[30,34–37]
Reduction of search/rescue space	[38]
Communications with civilians	[26,27,32,33]
Assessment of civilians status	[31]
Optimization of search/rescue cost	[45–50]

Figure 1 summarises the cost incurred as additional features and benefits are included in emergency response systems. wireless sensor network (WSN)-based emergency evacuation systems collect multi-domain sensing information to provide navigation services in a fully distributed manner and offer in-network knowledge discovery to respond to emergencies. This type of system relies on prior deployment of information and localization support. Decentralized evacuation systems offer better network resilience, scalability and lifetime, because they treat the sensing system separately from the decision system to prolong network lifetime and, also, involve mobile clients in sensing to adapt to intermittent connections and uncertain environments. However, this type of network must be supported by functionally separated system management and opportunistic networking and computing to extract the knowledge behind short-lived pieces of data. Agent-based simulators can help discover deep knowledge and conduct prediction and forecasting. Grid and cloud supported systems can provide parallel and auto-scaling computation to respond to emergencies. However, such systems must rely on a well-designed parallel programming model to divide adequately distribute computation tasks and Internet support. By involving more mobile entities, search and rescue systems can provide a richer response in case of emergencies using heterogeneous resource integration and control. In all these cases, we see that there is always a tradeoff between the quality and speed of the response to an emergency and the cost and sophistication of the technology.

We also need to consider the similarities and differences between indoor and outdoor emergency response systems. Both indoor and outdoor cases present similar challenges mentioned in Section 1, but existing technologies for indoor systems are quite distinct from those for outdoor systems. Table 2 compares indoor and outdoor systems with respect to the technical challenges mentioned in Section 1. In addition to WiFi, 3G and wired networks, short-range ZigBee and Bluetooth technologies are also useful in an indoor system. For information acquirement and dissemination, outdoor systems can benefit from rich information sources emanating from crowds. Localization in indoor systems can rely on RFID, RF

or sensor-based positioning, while GPS, WiFi and GSM positioning technologies are useful in outdoor systems. The dynamics of emergencies in indoor systems can be predicted using purpose built or tuned simulators, which can be run in a decentralized way, while centralized prediction and forecast are often conducted on back-end servers in outdoor systems. Heterogeneous system integration and asynchronous control are usually distributed in indoor systems, but centralised in outdoor systems.

Figure 1. A cost-benefit analysis of emergency response systems.

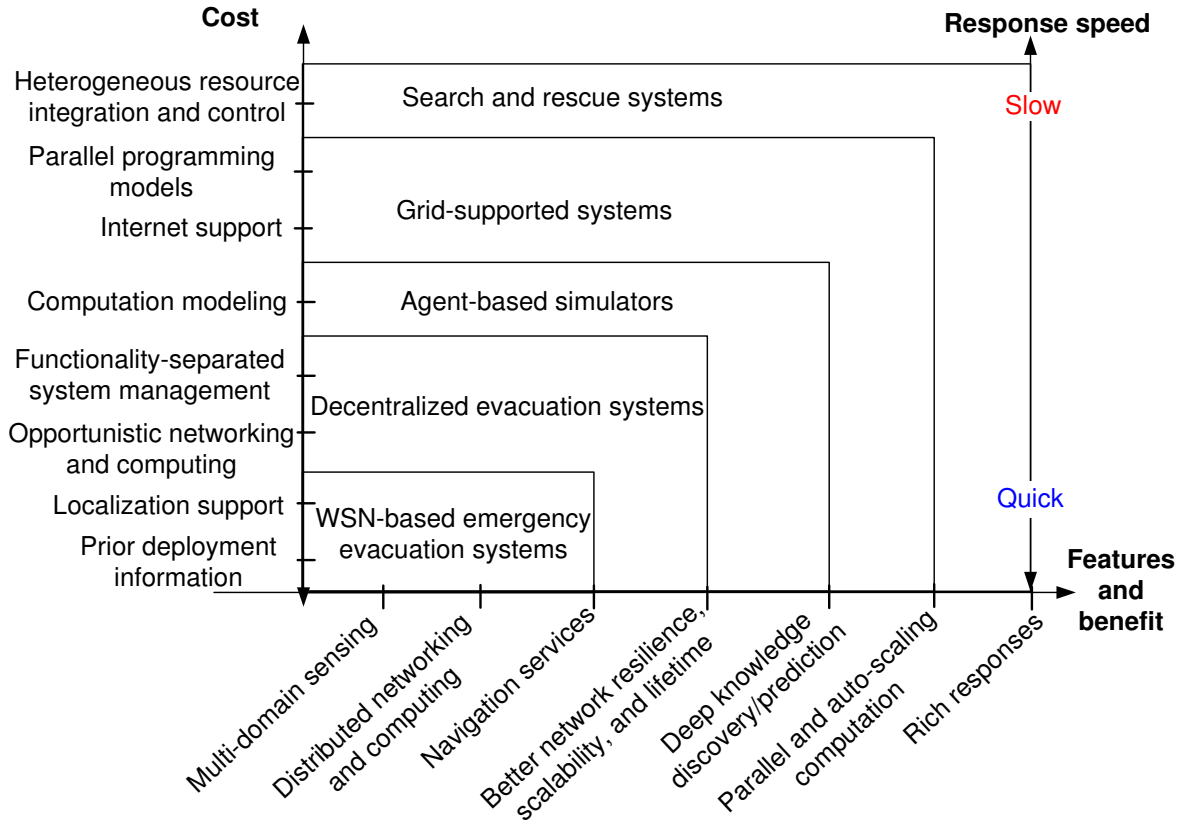

Table 2. A comparison of indoor and outdoor evacuation and rescue systems.

Technologies/system type	**Indoor evacuation and rescue systems**	**Outdoor evacuation and rescue systems**
Communications and networking	ZigBee, WiFi, Bluetooth, 3G, wired networks	WiFi, 3G, wired networks
Information acquirement and dissemination	clients and dissemination	crowdsourcing information
Knowledge discovery	RFID, RF or sensor-based positioning Decentralized predication	GPS, WiFi, GSM positioning Centralized prediction
Resource allocation and management	Localized dispatching	Centralized allocation
Heterogeneous system integration and asynchronous control	Distributed	Centralized
Existing technologies	[12–29,31–37,39,41,42,45–50]	[30,35,38,40,43,44,50]

4. Evolution towards Greater Complexity

Research on emergency evacuation systems has evolved from the simpler to the more complex, starting with homogeneous systems, which evacuate people with the help of a distributed WSN. This type of system emphasises in-network intelligence to find safe evacuation paths based on sensing data.

Then, we have moved toward a heterogeneous emergency evacuation system which separates functionalities into a distributed decision system and a sensing system to overcome the limitations of a homogeneous system. The sensing system will report multi-domain sensing information from mobile user clients and sensing clients to the distributed decision system so as to facilitate the interaction among the cyber and physical worlds. The third approach takes advantage of parallel agents to achieve fast-than-real-time prediction and discover deep knowledge. The fourth emerging approach relies on Grid computing technologies to find out contextual information for decision makers and handle a huge amount of data to predict dynamic hazard in a parallel way.

Finally, by introducing intentional mobility to emergency response systems, mobile entities are exploited to design more flexible and complex search and rescue systems.

Based on this evolution, we will discuss the issues on communications, information acquisition and dissemination, knowledge discovery, heterogeneous system integration and asynchronous control.

As the system becomes more complex, it can provide more precise prediction and decision, deeper knowledge, large-scale emergency support, and richer emergency response and bring better scalability, flexibility, system lifetime, and fault-tolerance. However, a more complex system relies on much more prior knowledge and complex technologies which will involve hardware costs and overheads in terms of network integration, cross-network communications, cross-machine computation, data management, networking infrastructure, distributed system management, integration control among diverse entities, resource management, and deployment. As different approaches aim at different objectives, open problems are still stimulating new research activities in emergency evacuation and rescue systems. For a WSN-based emergency evacuation system, if nodes break down or are moved by the hazards, system resilience and quality of information [52] are of concern. In addition, while most existing studies aim at an indoor system, an emergency evacuation system for outdoor and underground environments are also needed.

Since decentralised evacuation systems improve network lifetime and scalability by separating the sensing system and decision system but new network security risks such as Denial of Service also emerge [53]. Opportunistic networks (OppNets), opportunistic sensing (OppSense), inter-device security, and collaborative intelligence stimulate novel communication and computing paradigms. As contact duration among devices is limited (*i.e.*, limited bandwidth) and sensing data is collected intermittently, it is of interest to exploit the limited bandwidth to exchange information with the highest knowledge reward [54], assure security of information exchanges, and discover knowledge behind short-lived and intermittent data to enhance system intelligence in a self-contained way are challenging problems.

While agent-based simulators offer the capability to discover deep knowledge from learning [55] and behind collected data, human behavior modelling, augmented reality [56], activity analysis and inference, and social behavior in emergencies can be considered to enhance system intelligence. As

Grid or cloud supported systems can improve the system scalability, managing big data (a huge amount of data) is inevitable, and data analysis technologies will need to incorporate multi-domain information (for example, localization technologies may consider low-accuracy WiFi/GSM information to compensate for the lack of high-accuracy GPS). As search and rescue systems involve diverse mobile entities (e.g., robots and smartphones), cross-system integration control, intelligence learning for mobile entities in an OppSense environment, and more complex distributed computing in OppNets become challenging.

5. Emerging Challenges and Opportunities

In this section, we will point to some technical challenges and opportunities for future emergency response systems and discuss related technical progress that has been made. Table 3 summarises the pros and cons of emerging technologies and open research problems from different perspectives.

Emerging technologies for heterogeneous network integration emphasize compliance with standardds that open an opportunity to integrate WSNs with other networks. However, current technologies still rely on gateway nodes to transfer data. Since opportunistic networking is at the confluence of *ad hoc* networking and disruption tolerant networks, this recent technology requires a more seamless networking environment to allow intermittent communications between any pair of devices at any time and place. Since emerging sensing devices are equipped with multiple types of wireless interfaces (for example, a smartphone has 3G, WiFi and Bluetooth interfaces), a device may belong to multiple types of networks at the same time. Network virtualisation for devices will then choose the best communication network for conveying data seamlessly based on urgency, available bandwidth and communication cost. On the other hand, instead of node-centric networks, knowledge-centric network designs are needed to advance towards distributed intelligence. Thus, knowledge-driven solutions will steer collaboration between several networks to integrate knowledge extracted from diverse data sources.

Regarding security, emerging technologies can offer secure communications between devices only when they have the same sensing signature. This approach facilitates automatic authentication between devices and secure pairing of devices in physical proximity. However, these technologies aim at device-level information sharing rather than content-level information sharing. Once devices authenticate each other, complete trust between devices may expose the system to malicious attacks (e.g., drop-all behavior, random RF jamming and dissemination of false information) [57] in an opportunistic networking environment. Thus, the security of opportunistic communications becomes an open issue in emergencies. Regarding privacy, emerging technologies pull service content to avoid pushing private information, so as to keep private data sets separate from public data. Although these technologies provide system-defined privacy to isolate personal private data, user-defined privacy and multi-level privacy are not provided, and activity inferences are a risk to personal privacy. As emergency response systems must rely on diverse data sources, there are important open issues on knowledge inference in connection with trust, security and privacy.

Table 3. The technical progress and open research problems toward cyber-physical evacuation and rescue systems.

Technical scope	Advantage	Disadvantage	Open research problems
Network integration	• interoperability with wireless sensor networks (WSNs) • compliance with networking standardds	•integration via gateway nodes	• seamless OppNets • networking virtualisation • knowledge-centric networks
Security and privacy	• proximity-based authentication • pull-based service content • separate private data sets	• device-level sharing • only system-defined privacy • divulgence of privacy by inference	• security of opportunistic communications • privacy-preservation knowledge inferences • trust, security,and privacy in mobile systems
Mobile sensing systems and Cloud-enabled decision systems	• knowledge from the wisdom of crowds • scalable sensing/decision-making model • optimization of task migration	• simple activity inferences • one-way knowledge flow	• participatory and collaborative sensing models • energy management of mobile devices • QoS-guaranteed cloud and big data in cloud • load-balancing simulation models

While emerging technologies pay attention to mobile sensing systems incorporated with cloud-enabled decision systems, they can also take advantage of information contributed by the crowd to find out the knowledge behind a huge amounts of sensing information. Only scalable decision-making models or bio-inspired approaches [58] are able to handle such a huge amount of data, and emerging technologies must pay attention to data optimisation and to migrating the computation between physical/virtual machines.

Although a simple learning process can suffice in certain cases (e.g., identification of user mobility using GPS data only), more complex learning and inference from human activity is needed using different ambient signatures including audio, location and social network information. However, as these technologies only consider one-way knowledge flow from data from the sources to the back-end cloud, a novel two-way knowledge feedback loop from cloud to clients may facilitate not only knowledge discovery, but also sensing optimization. Designing participatory sensing and collaborative sensing models [59] is also a challenging problem. The control of sensing with one or more groups of people, devices, networks and systems may contribute a single piece of location information or a summary [60]. Cloud-assisted collaborative sensing can then control the sampling rates of sensors to achieve a required level of accuracy.

The tradeoff between data quality and quantity collected by mobile devices also raises open research issues of energy management for mobile clients. QoS-guaranteed networks and systems also raise challenges in emergencies especially for time-constrained and resource-constrained responses. A cloud-related service's service-level agreements (e.g., response time), the scheduling of concurrent tasks, parallel programming aspects and big data processing and management all create challenging performance problems.

Another important aspect in emergency management is the appropriate balance between simulation, which is extensively used, and modelling using probability models [61,62], which was first suggested many years ago [63], but which has been very seldom used. Simulation will necessarily be time consuming, both in programming and development to incorporate new features and details and in run time. Mathematical models can potentially be much faster, but require significant computation to obtain

the normalising constants that are needed to compute all the event probabilities. Some recent promising work [64,65] indicates that graph theoretic models, as well as queueing theory, can help identify the most vulnerable or busy areas of an evacuation scene. Open queueing models can also provide lower and upper bounds to evacuation times and have the potential for providing insight in a computationally fast manner into the major bottlenecks and the time bounds related to an evacuation, and this analysis can also lead to further research on task and resource assignment algorithms [66] for emergencies. We feel that there is an opportunity for more work in these directions.

5.1. Network Integration

As a cyber-physical emergency response system may have to rely on cooperation among multiple networks, the integration and interference avoidance, among heterogeneous networks emerges as a significant issue.

Progress toward network integration standardds: IP is not adequate as a standard for WSNs, and TinyOS [67] deviates from IP and has to be lightweight for power-saving purposes. The uIP [68] concept includes a low-power link built on IEEE 802.15.4-embedded devices to avoid a heavyweight IP stack. The IETF defines the RFC 4944 (6LoWPAN) [69] to allow IPv6 datagrams to be carried over IEEE 802.15.4 frames by fragmentation and header compression. In [70], a IPv6-based network architecture is proposed to support duty-cycled link protocols, hop-by-hop forwarding and efficient routing protocols in WSNs. Multiple WSNs can be connected by *border routers*, which can forward IP datagrams, where each border router may also implement IPv4-to-IPv6 translation in compliance with conventional IPv4 networks. The emergence of WiFi Direct [71] allows mobile phones to exchange content directly based on peer-to-peer communications.

Interference avoidance among heterogeneous networks: communication reliability becomes more difficult when multiple networks co-exist., e.g., WiFi, Bluetooth and IEEE 802.15.4 networks. References [72,73] describe performance degradation in ZigBee networks that co-exist with WiFi networks. The major reason is that the ZigBee signal is too week to be detected by WiFi senders. Many efforts consider a pessimistic mechanism to *avoid* using the channels occupied by other coexisting networks. In [74], superframes of multiple coexisting ZigBee networks are scheduled, while [75] allows a node to use different channels at different time points. In contrast, [76] proposes a header redundancy scheme to reduce *header corruption*, where multiple headers associated with a single ZigBee packet are sent. Since WiFi packets are typically shorter than ZigBee packets, longer ZigBee packets may cause WiFi transmitters to back off and shorter WiFi packets may corrupt ZigBee packet headers. Using a multiple header scheme, the first (corrupted) header can cause a WiFi transmitter to back off, and the second header can improve the correctness of detection by a ZigBee receiver. To reduce the number of forwarding messages between multiple mobile networks, the approach in [77] proposes a mechanism to detect the overlapping structure among them based on their density and the degree of connectivity. Interoperability among several heterogeneous networks is facilitated by a gateway selection scheme proposed in [78].

5.2. Security and Privacy

As part of the essential needs for emergency management, sensing data cannot belong solely to individuals. Security and privacy issues thus become more important and challenging.

Cyber-world security: in case of emergencies, wireless mobile devices may need to interact when they encounter each other. Security thus becomes more important than in other cyber-physical systems. Secure pairing of mobile devices [79] allows mobile devices to simply shake (or sense) together, as in earthquakes, so as to construct a common cryptographic key based on data from accelerometers. Such approaches may not always work in emergencies. Instead of authentication by shaking, in [80], two mobile devices are allowed to share data only when they are in proximity of each other. A shared secret key will be generated automatically between the two devices based on their common ambient wireless signals. Mobile devices close to each other will perceive similar fluctuations in wireless signals, whereas they will perceive different fluctuations in wireless signals for devices further away from each other. In this way, mobile devices can authenticate with each other and, thus, secure data exchanges that are freer from malicious attacks (e.g., remote terrorists). As cloud computing boosts many promising services, several efforts focus on the security issue of back-end cloud centres. A conventional way is to encrypt (resp., decrypt) each piece of data before data contributors (resp., consumers) push (resp., pull) the data. In [81], the *user revocation issue* is discussed; it involves the overheads for key redistribution and data re-encryption when a data contributor wants to revoke some data consumers' access privileges (for example, civilians may revoke pushed data after leaving form emergencies). In this work, each data contributor provides the cloud with a re-encryption key for each valid data customer, where the re-encryption key also helps transform encrypted information between each pair of contributor and consumer. Once a data customer is revoked by a data contributor, the data contributor simply commands the cloud to destroy the re-encryption key so that no overhead is incurred, due to key redistribution and data re-encryption. In practice, multiple types of emergency services (e.g., evacuation in fire events and rescue in earthquakes) may need to collaborate with each other or share resources. Considering the intra-cloud and inter-cloud security, [82] relies on a trusted third-party agreement government to provide all collaborating services with a contract, so as to enable secure communications between multiple services.

Physical-world privacy: as location-based services rely on location information of mobile users, evacuation and rescue applications need even more accurate location information of civilians, raising the issue of privacy. Instead of keeping the detailed locations of mobile users in back-end servers, the approach in [83] pre-fetches location-enhanced content (e.g., a local map) into mobile devices and caches it in advance before it is actually needed. When evacuation and rescue applications require the content, it is retrieved from the cache rather than pushed from the location of civilians with a live query. Due to mobility of civilians, the information can be downloaded and updated at a favorable time (e.g., when WiFi connection is available). Since cloud computing can provide customers with seamless technologies to access distributed database systems (e.g., Amazon SimpleDB [84]), the work in [85] considers separating the user database from service servers for greater privacy. High-privacy data is only stored in the private service server, while the public cloud database stores low-privacy data.

5.3. Mobile Sensing and Cloud-Enabled Decisions

As smart phones become ever more present and cloud computing emerges as a dominant technology, crowdsourced data in connection with cloud computing may greatly facilitate the evacuation and rescue systems of the future. Thus, we next discuss some emerging opportunities and technologies from this perspective.

Augmented reality with crowdsourced data: mobile phones are considered as simple clients in many evacuation and rescue systems, due to their sensing ability and popularity. Combining crowdsourced data with virtual or augmented reality on smart phones raises some challenges in terms of visual navigation directions, accurate positioning and aggregation of crowdsourced information. Visual navigation directions can annotate the direction of motion on smartphones to guide people clearly. Accurate localization systems guarantee precise positioning of victims, which cannot be supported by the low-accuracy GSM positioning technology. Aggregation of crowdsourced information provides first responders and victims with the wisdom of crowds.

Since people in a disaster are usually under stress and likely to be confused in [86], mobile phones guide users to the exit by using 3D building models augmented with visual evacuation directions based on the evacuees' current positions and environmental situations in the building. Two important technologies, localization of victims and visualization of 3D building, are addressed in the system. The localization of victims relies on an active RFID system, while the 3D visualization is based on a mobile 3D rendering engine. Instead of a virtual building model, *Augmented Reality (AR)* guiding technologies could be preferred in emergencies, especially for people who are unfamiliar with the environments. Instead of costly RFID infrastructure, the work in [87] implements an infrastructure-less emergency evacuation system, which adopts built-in sensors on smartphones (e.g., accelerometers, cameras and digital compasses) and image-based localization technologies for flexibility and scalability purposes. The back-end server localises victims by matching image snapshots with well-known locations to provide them with uncrowded paths, where well-known locations could be crowdsourced labels. Since existing map providers (e.g., GoogleMaps) provide only roads or building shapes without enough information about the connection points between buildings and roads in the real world, in [88], a crowdsourced map which allows users to contribute evacuation routes between buildings and routes, so as to provide a more accurate environmental model for evacuation simulations, is suggested. Similarly, [89] provides volunteers with a crowdsourced map to tag information on incidents that need rescuers' attention.

Cloud-enabled decision systems: as massive and multi-domain data need to be processed quickly in emergency response systems, cloud computing may be adopted to design more satisfactory systems with higher processing speed, larger storage memory, less risk, lower cost and higher capability for integration. In [90], computation tasks, including RFID-based positioning, calculation of evacuation paths and database management, are migrated to a back-end cloud platform. Considering urban-scale emergencies (e.g., earthquakes or tsunami disasters), [91] considers a cloud-enabled vehicular emergency response system to evacuate people from city. This system consists of three layers: (1) cloud infrastructure layer; (2) intelligence layer; and (3) system interface. The cloud infrastructure layer adopts a Xen hypervisor to provide a parallel and distributed architecture. The intelligence layer is deployed computational models and algorithms to process multi-domain data and make decisions on evacuation

routes based on density and velocity of vehicles. The system interface acquires data from the vehicular networks via mobile phones or roadside communication units. Since the data and emergency response resources (e.g., hospitals, rescuers, volunteers, polices and emergency management organizations) may belong to different organizations and need to collaborate with each other in case of emergencies, [92] introduces the concept of social networking to construct a community-based emergency management system on the cloud. In this system, the cloud centre has two major components, *information repository* and *social networking*. The information repository manages the emergency response resources and collects the data of emergent situations from social networking, while the social networking provides users with access interfaces to interact with each other.

QoS in the cloud: For scalability and fault-tolerance reasons, MapReduce provides a parallel and distributed programming model to process massive amount of data. Hadoop is one of the most commonly-applied implementations of MapReduce to enable the virtualisation in the cloud. As a multi-core CUPis involved, Hadoop exploits virtualisation technologies to deploy multiple virtual machines (VMs) in a single physical machine, so as to speed up data processing in cloud. Work [93] exploits the above advantages to divide each database query into several subqueries in MapReduce for quick recovery from mid-query faults. However, I/O tasks between VMs may incur overheads, especially for I/O-intensive applications. Thus, how to reduce I/O tasks becomes a critical challenge in the cloud. Reference [94] allocates data across all VMs based on the data locality to reduce I/O overheads. To relieve the waste of network bandwidth, due to communications between VMs for I/O-intensive applications, [95] proposes a *decentralized affinity-aware migration* technique that monitors fingerprints of traffic exchanges between VMs and dynamically adjusts/migrates VM placement for communication optimization. In addition to optimization of data distribution in the cloud, some efforts address the QoS issue on virtual machine provisioning, which emphasises how many virtual machine instances should be allocated to an application for achieving QoS requirements (e.g., response time). Obviously, virtual machine provisioning without over/under-provisioning and having unacceptable QoS is a challenge, because workload and runtime situations are highly dynamic. Based on an analysis of workload for each application, [96] proposes a prediction-based approach to determine the number of allocated virtual machines.

6. Areas for Future Work

This paper has discussed future research on emergency management systems that rely on sensor networks to locate hazards and also locate people, both evacuees and emergency personnel, and communications between evacuees and emergency personnel. These systems use distributed or cloud-based decision-making to make the best resource allocations and provide judicious guidance to evacuees.

Although we have tried to conduct a comprehensive review, there are several significant areas that we have not discussed and which require much more attention and research. We have seen that EMSsare intrinsically distributed, so that in the future, we may see more related work on distributed control and distributed algorithms for such systems [97]. The information that is collected via sensing is often inaccurate and requires interpretation [52]. Events, such as explosions and the spread of fire, can take

place at a high rate and are themselves disruptive; thus, the limitations of sensing for EMS is definitely a topic that requires much more attention. A distinct, but related, problem is the manner in which one may be able to interpret items of information that are biased (e.g., information from people under the effect of fear or shock) or that is driven by different objectives (e.g., providing information to reduce panic) [60]. Much further work is needed in these areas with a specific focus on EMS.

The consequences of either over-estimating or under-estimating the resources needed during an emergency can both be dire. In addition, the optimum allocation problems are themselves NP-hard. Even worse, they typically need to be taken in real-time, based on incomplete or partial information [50]. This is yet another research area for EMS systems that merits much more attention.

Another important topic that has been neglected so far is the use of probability modelling [61,63,98] for emergency events that are intrinsically probabilistic, and where one seeks evaluations, which are necessarily statistical or probabilistic. Such methods can help us reduce or avoid lengthy computer simulations. An advantage of such approaches is that they can provide a computationally fast mathematical prediction of the overall performance of algorithms and policies [64], prior to lengthy simulation studies or experimental evaluations, even though the mathematical analysis may not be able to include all relevant aspects. We think that such methods will become more prevalent as the study of EMSs gains prominence and joins the mainstream of human based cyber-physical systems.

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