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A user centred design evaluation of the potential benefits of advanced wireless sensor networks for fire-in-tunnel emergency response

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ABSTRACT

This study aimed to assess, from an end-user perspective, the potential role of reconfigurable wireless networks in responding to a fire-in-tunnel incident. The study was based on a multi-media, scenario-based simulation of an incident, and assessment of the benefits and drawbacks of the new technology by subject matter experts in relation to their operational goals, with particular emphasis on support for situation awareness. Advanced wireless networks were shown to have considerable potential for improving the effectiveness, efficiency and confidence of emergency responders at various phases in a fire-in-tunnel incident, due to access to more accurate, complete and reliable information. A key requirement was to ensure that new technologies provided the *right* information, not just more information, at the point of need.

1. Introduction

1.1. Background

Situation awareness (SA) is recognised as a key requirement for effective decision making in emergency response [1]. In certain types of incident, such as a fire in a tunnel, it is difficult for emergency responders to develop and maintain SA due to dynamic nature of traffic, the lack of line of sight to the incident, the obscuration of the scene (and CCTV) by smoke, and potential damage to power, communication and monitoring networks. SA has been identified as a key issue in major incidents such as the World Trade Centre disaster [2]. Limitations in the information available at an emergency – and hence difficulties in developing and maintaining SA – have been shown to lead directly to decision making failures by the fire and rescue service [3].

Although a range of sensors are available [4], traditional wired networks have drawbacks in terms of installation time, overall cost and flexibility in tunnel environments [5]. Emerging technologies, such as advanced wireless sensor networks (WSNs), have the potential to enhance the information environment in order to increase the SA during an incident, and help support decision making and other operational objectives during emergency response [6,7]. A WSN is defined as a group of specialized transducers with a communication infrastructure that can monitor and record data at diverse locations [8]. Sha et al. [9] argue that as long as specific research challenges – including: realtime self-organisation, fault tolerant routing, and realtime and mobile localisation – can be addressed, WSNs are a very promising technology for fire rescue applications, and there has been increasing interest in the use of WSN for fire detection and response [5].

Although new technologies offer potential for improved emergency response, a challenge is how to assess the benefits they could provide. IT-based innovation to support emergency response has been slow to be adopted by the emergency services [10,11], and end user involvement of emergency responders in the design of supporting technologies has historically been too sporadic [12]. It is beneficial to assess their potential impact at an early stage, before such developed systems actually exist, since this helps identify, with relatively low cost and effort, where the relative advantages and barriers occur, for enhancing emergency response. Despite the promise of new technologies, there has been concern that technology centred approaches to systems design focus on data provision rather than operational impact [13,14]. Carver and Turoff [15] call for a user-centred approach to the design of emergency management information systems, with an emphasis on user requirements. This perspective starts with the emergency responders, their responsibilities and operational goals, and their information needs. It focuses explicitly on the enabling properties of new technology, and the benefit that is provided to the end

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users. Early evaluation of prototypes is a key component of such approaches [16].

1.2. Aims

The main aim of the study reported in this article was to explore the extent to which advanced WSNs can potentially enhance emergency response in relation to key operational objectives during a fire-in-tunnel incident. This article uses a PACT (people, activities, context, and technology) [17] framework to design a simulation, that demonstrated the functional capabilities that advanced WSNs could provide during a fire-in-tunnel incident. A secondary aim of this article is to demonstrate how the potential usefulness of new technologies can be demonstrated and evaluated from a user centred perspective.

2. Literature

2.1. The need for situation awareness (SA)

SA is key to decision making in complex emergency response [1,18,19]. It is described by Endsley [20] as the 'perception of the elements in the environment within a volume of time and space, the comprehension of their meaning and the projection of their status in the near future', comprising Level 1 (identification of elements in the environment), Level 2 (interpretation of their meaning), and Level 3 (their future projection).

In essence, SA is the extent to which the perception of an environment by an individual is an accurate reflection of reality. In almost every time-critical and complex domain SA plays a key role in decision making and effective performance [21] and it has been shown that the faster incident commanders analyse and act on key information, the more effective their response will be [22].

Although high SA does not always lead to better decisions [23], it has been recognised that many shortcomings in disaster response operations are due to poor decisions made by first responders due to a lack of SA [24]. The official NIST report into the emergency response operations at the World Trade Centre disaster [2] concluded that 'situational awareness was an overriding issue with all emergency responders during the WTC operations', and that either too much, or too little information on the situation 'prevented responders from having adequate, accurate, and timely information for decisions that were critical to operations and may have been critical to life safety…'.

2.2. Properties of emerging wireless sensor networks

Advanced WSNs have several advantages over fixed networks within an emergency response scenario in a tunnel [5]. They are more easily reconfigurable and scaleable, and the network can be made more flexible due to the lack of requirement for hardwired connections. Their primary disadvantages are increased cost, being fault prone [25], and limitations in battery life. Advances in WSNs mean that data networks can now display a number of properties which mean they are better able to support emergency response to a fire-in-tunnel scenario. These properties can be capitalised on within both the preparedness and response phases of emergency response, as outlined in Table 1 below.

Ahmed and Sugianto [26] investigated the potential benefits of adopting RFID within emergency response, and highlighted the need for 'acquiring robust technologies which can work consistently in unfavourable working conditions'. Other examples of the proposed applications of advanced WSNs in emergency response include: reconfigurable architectures for heterogeneous embedded systems [27]; adhoc networks for situation management [19]; monitoring location and vital signs of firefighters [28]; help with evacuation [29]; use of robots to introduce new sensors into a network [30].

These contributions highlight the technical capabilities of advanced WSNs, and particularly those that are reconfigurable. However the literature lacks investigation of the potential impact of WSNs on the wider operational capabilities of first responders, and this early (and therefore low cost) evaluation of the effectiveness of future technologies within emergency response contexts is illustrated in this article.

3. Methodology

3.1. Theoretical perspectives

This article takes a user-centred [31], rather than technological perspective and places the emergency responder at the focus of interest. A user-centred design (UCD) perspective is increasingly being used within multidisciplinary design and research teams, in order to establish the impact of new technologies. With user-centred systems design a key principle is early end user evaluation of prototypes which are used to visualise and evaluate ideas [16].

A value-added approach [32,33] was used to theoretically compare the information environments provided by fixed networks and the potential capabilities of a WSN. The potential benefits of each during emergency response are shown in Fig. 1, representing the difference in outcomes that can result when a limited or degrading information environment is maintained or supplemented by a WSN.

A goal-directed approach was used to establish the link between individuals, the operational objectives at different stages within a fire-in-tunnel scenario, and their information requirements. Within human–computer interaction (HCI), task analysis has been used for many years to help understand the activities that individuals undertake and their motivations for doing so [34]. More recently, new frameworks have been developed that make a more explicit link between user goals and information needs [35,36].

The final theoretical consideration was the nature of the outcome metrics that would be used to compare different technology-enabled scenarios. A usability evaluation framework was used where usability is defined as 'the extent to which a product can be used by specified users to achieve specified goals with effectiveness, efficiency and satisfaction in a specified context of use' [37]. Usability has been established within the HCI literature for many years [38], and is particularly suited to work-based IT implementation where tasks and goals are relatively easy to define, and where the time or other resources needed to undertake those tasks are important.

The usability standard [37] highlights the importance of ensuring that the correct individuals take part in evaluations, the need for a realistic environment, and clear definition of important goals or operational objectives. The focus on goals is also consistent with SA being defined according to the goals and decision requirements for a particular job [39,40]. The main operational objectives were defined for the individuals involved in each of the scenario stages, and the usability of the WSN was assessed in relation to each of these objectives (see Table 3). The rationale for the scenarios, and their design, are described below.

3.2. Scenario design and validation

Scenario-based approaches have been used for over 20 years to envision the end user within a realistic context of use during system design. Their key strength is that they define how an