# OPPORTUNITIES AND CHALLENGES FOR CONFIGURABLE SENSOR NETWORKS FOR ENABLING EFFECTIVE FIRE-IN-TUNNEL RESPONSE

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## Abstract

Recent fires and resulting casualties in major road tunnels have highlighted the need for both better safety precautions and the need for a more effective emergency response during an incident. More complete, accurate and relevant information during an incident can increase the effectiveness of the response by the emergency team. Although traditional sensor networks (eg those detecting smoke or fire or enabling data transmission) can help supply information, they may be susceptible to damage and are relatively inflexible. The dynamic reconfiguration of sensor networks provides an opportunity to increase the quality of the information environment at a fire in tunnel (or other disaster) situation. This reconfiguration can include: switching between wired and wireless links to mitigate physical network damage; repurposing of sensor nodes to change what they sense or how quickly they report; introduction of new mobile gateways for self repair of network damage; and the integration of multiple mobile sensor networks (eg personal sensors worn by emergency crew, or those introduced by autonomous robots).

The effectiveness of this reconfiguration is determined by the extent to which it supports the needs of the emergency response team during a fire in tunnel incident. A series of field studies was undertaken to identify both opportunities and challenges in this respect. Particular opportunities for enhancing the information environment were: providing a capability to 'see' through the smoke; accounting for vehicle occupants during an incident; managing hazardous goods; tracking the movement of emergency workers; monitoring of the tunnel infrastructure; and transmitting advance information to fire crews. However, there were also some potential barriers, including: scepticism of emergency teams due to concerns over reliability, cost,

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maintenance and false alarms; the reliance on existing visual information at scene; the needs of a hierarchical and clearly defined command, control and operational structure; and the individual and collective responsibilities during an incident. The implications for network reconfiguration are discussed.

## Introduction

Recent disasters, including flooding, fire and explosion, have highlighted potential for loss of life, and the need for an effective emergency response to these disasters. Although in many cases the initial incident may not be preventable, a fast and effective strategic response by the emergency services can minimise loss of life and damage.

Road tunnels are a good example of where safety features can be incorporated to (1) reduce the likelihood of incidents occurring, (2) minimise the likelihood of minor incidents turning into major disasters, and (3) assist the emergency services when responding to an incident. There are several recent examples of fires in road tunnels where there has been loss of life, for example the Mont Blanc road tunnel in 1999 where 39 people died.

There are various operational conditions that are typical stressors on firefighters during an incident such as a fire in tunnel, including ambiguous and incomplete information, particularly during the early phases on an incident (Danielsson, 1998, Danielsson and Ohlsson, 1999). It may not be clear what the nature and extent of a incident is, how many casualties or potential casualties are involved, where potential escape routes are, and what further risks are present.

Embedded sensor networks have the potential to enable a better state of 'preparedness' prior to any incident, provide an early and reliable alarm if an incident does occur, and support a more effective response by the emergency services throughout the course of an event. A broad definition of sensors is used to describe the ability to describe or measure absolute and relative properties or attributes of entities within an environment. For a tunnel environment, this would therefore include measurement of physical properties such as heat and smoke levels, the nature and location of dynamic entities such as vehicular traffic and personnel in the tunnel, visual data such as CCTV images (visible or IR spectrum), and data that allows the placement of these entities and attributes on a 'map' of the incident.

There is currently much interest in providing real-time information to emergency responders during an incident. For example the FIRE project (http://fire.me.berkeley.edu/about_fire.htm) is applying and designing new technologies such as wireless sensor networks (WSNs) and small head-mounted displays (HMDs) for firefighting in order to compliment existing and proven methods of firefighting.

However, the data that can be supplied to emergency teams is dependent on a robust sensor network. During the course of an incident, there is likely to be damage to networks which can render fixed networks inoperable. Fire in tunnel incidents have demonstrated the catastrophic impact on emergency responders of the technical failure of systems. In addition, since incidents are highly dynamic and often unpredictable, fixed sensor networks may not offer the flexibility needed as an incident develops.

There are a number of implications for sensor networks that are effective within a fire in tunnel (or indeed other) emergency scenario. They should be robust to cope with a demanding environment and adaptable to support dynamic needs. This implies networks that:

- are 'self healing' when damage occurs
- can be reconfigured to alter what they measure or how they report data
- can be scaled up or down successfully as sensors leave or join the network
- are able to operate within a highly heterogeneous environment (eg different kinds of fixed, mobile and embedded sensors, different operating systems)

Current constraints to creating these robust, ubiquitous and heterogeneous networks are largely software related. In particular, there is a lack of a consistent, generic programming platform that enables the creation of these networks.

The RUNES project (www.ist-runes.org/) is addressing the issues above. It is a large-scale European technology development project, the aims of which are to provide the software platforms and development tools to enable the creation of reconfigurable networked embedded system.

To demonstrate the potential benefit of advanced sensor networks, a fire in tunnel scenario is being used – it is a challenging environment where dynamic information provision is critical to effective emergency management (ie being in a state of 'preparedness', incident response and 'post mortem'). A key part of the project has been to understand the requirements of the stakeholders involved in emergency management within a fire in tunnel: the technological development within the project is therefore being married to a user-centred design approach. This paper summarises key technological features, and describes opportunities to impact on stakeholders concerned with emergency response.

## Technology overview

The RUNES EU funded project is focused on the creation of software tools that will enable the construction of systems which create or utilise existing large heterogeneous networks of computing devices. The devices may range from single function sensors such as temperature or light, up to full multifunction workstations with extensive resources and computational power. The networks may range from large fix wire communication systems to local wireless connectivity such as Bluetooth. More detailed explanation can be found in Coulson et al., (2006).

At a general level, RUNES addresses four key aspects of a heterogeneous, embedded sensor network:

**Autoconfiguration:** The automatic configuration of devices without manual intervention, without any need for software configuration programs or jumpers. Ideally, auto-configuring devices should just "Plug and Play".

**Configuration:** The setting of the parameters of a device provided through the device's interface for achieving a desired behaviour in the operational range of the device.

**Preconfiguration:** The configuration of devices either in advance of their deployment or in advance of a scenario actually developing, using whatever manual intervention is necessary.

**Reconfiguration:** The ability of a system to change its configuration on the fly; either in response to particular commands given manually, or in a semi- or fully-autonomous manner to achieve a particular mission critical objective - which might vary from reporting information in an accurate or timely way to maintaining connectivity.

Within a specific application context, the network configurations outlined above provide a range of basic capabilities to a stakeholder within a particular environment:

1. Maintaining the integrity of the data within an information environment
2. Providing additional information to the information environment or widening the information environment
3. Changing the purpose of the information environment to suit specific needs
4. Optimising the efficiency and functions of the information environment

From a user's perspective, an advanced sensor network acts to supplement, maintain or enhance an information environment. However, the underlying technology will be relatively transparent to an end user (eg tunnel manager, control room operator, emergency response team or tunnel user).

## Theory and method

This article is written from a user-centred design perspective, eg. Preece et al., (2002). Although it discusses potential technologies, the underlying interest is in determining the potential impact of technologies on one or more end users. Effective technologies need to impact positively on user outcomes – ie consistent with a 'realised value' outcome from an information science perspective, as described by Ahituv et al., (1998).

A series of field visits were undertaken to understand opportunities for advanced sensor networks to impact on a fire in tunnel incident. This data collection was based on a review of tunnel fire incidents and safety initiatives (eg UPTUN: Cost-effective, Sustainable and Innovative Upgrading Methods for Fire Safety in Existing Tunnels, http://www.uptun.net/), interviews with stakeholders and field visits to four different road tunnels: the Øresund bridge/tunnel link between Denmark and Sweden; the Mont Blanc tunnel between France and Italy; the Kent (UK) Dartford and Medway tunnels; and the Elbe tunnel in Hamburg.

During these visits, a variety of user needs were discussed with tunnel health and safety managers, operations managers and fire service commanders who had specific responsibility for responding to incidents in those tunnels. The following is a summary of opportunities and challenges that arose from these discussions. 'opportunities' are used to describe where there are relatively unequivocal benefits to stakeholders, 'challenges' describe where there are potential benefits but concomitant challenges to successful introduction.

## Results – *opportunities* for advanced sensor networks

### *Opportunity #1 'Seeing' through the smoke*

*Problem summary:* Smoke in the tunnel is always treated as a major incident as it presents the greatest threat to personnel in a tunnel when there is a fire. However, smoke in the tunnel quickly renders the CCTV that is used by the tunnel Operators useless. Even 'white' smoke from car engines that seldom leads to a fire obscures the CCTV and causes extreme visibility problems for tunnel occupants, tunnel supervisors and emergency workers. In addition to the obscuration due to smoke, it can be difficult to identify the nature of smoke, and track its rate of progress.

*Proposed technological solution:* The use of networked embedded technologies to distribute and maintain the transmission of data acquired from location sensors during system damaging scenarios; to enhance the information by the integration of more location sensors; enable the incident (including objects) to be sensed or 'seen' when all visual capability is lost through smoke propagation.

*Usability (operational) aspect:* To impact on operational goals of situation assessment and response, including casualty rescue.

*Stakeholder feedback:* This capability of 'seeing' in the smoke was suggested by both health and safety fire commander stakeholders and may be their greatest need if there was a serious incident. There are some solutions available (eg infrared helmets that fire fighters can use) but they are expensive, are infrequently needed, and are another piece of equipment that must be carried and maintained.

### *Opportunity #2 Managing hazardous goods*

*Problem summary:* There is a lack of information on hazardous goods travelling through the tunnel. This has implications for safety management, regulation compliance and emergency response.

*Proposed technological solution:* The use of electronic tagging of cargos and/or intelligent hazard plates that can be read by sensor networks. The use of networked embedded technologies to distribute and maintain the transmission of data acquired from electronic tags relating to the type and quantity of hazardous goods being carried through the tunnel,. The integration of the cargo sensors into the wider tunnel network.

*Usability (operational) aspect:* There are three distinct uses for this information – (1) strategic goods transportation risk assessments based on accurate and complete historical data; (2) accurate identification of hazardous goods (conformance) during normal operation; (3) emergency response (preliminary and ongoing situation assessment) during a fire in tunnel or other incident.

*Usability (operational) aspect:* Impacting on operational goals of risk reduction (pre-incident), preparedness, and situation assessment.

*Stakeholder feedback:* This issue was particularly pertinent to the individuals with health and safety responsibility. Tunnel management will typically ban the passage of certain hazardous goods, and limit the passage of other hazardous goods to night time when the traffic levels (and hence risk) are lower. A variety of approaches are used, ranging from escorting hazardous goods, limiting their passage, pre-entry vehicle checks and relying on self-compliance with regulations in place. A constant concern is that drivers are either unaware of the nature of their cargoes (especially for mixed loads), are unaware of the restrictions put in place, or even actively flout the restrictions by temporarily removing the hazard plates to allow unrestricted passage. At one tunnel, where hazardous goods passage was restricted to the night time, the tunnel operators discovered 10-20 lorries a month with hazardous cargoes travelling during the daytime. However they were well aware that there were others with plates on that they didn't discover, and others without plates that were deliberately flouting the passage regulations for hazardous goods. More accurate data on the types, frequencies and travel patterns of hazardous cargoes would enable better planning of restrictions for this traffic (eg diversion of hazardous cargoes via the ferry). Automatic identification of hazardous cargoes would also enable better enforcement of the travel restrictions.

From a fire commander perspective, there was also a lack of information on hazardous goods, which could be vital for putting into place an effective response to an incident. The information on the hazard plates is used to determine an appropriate responses (eg some chemicals can explode if water is put on them!). Within tunnels, this information can sometimes be obtained from the tunnel control rook using CCTV, but this depends on the orientation of the lorry in relation to the cameras. Other options on arrival are to ask the driver or passengers, but this depends on effective communication links in the tunnel.

***Opportunity #3 Tracking/managing movement of fire fighters***

*Problem summary:* If a fire commander is not at scene, or if the incident is large or smoke obscured, it is difficult for them to direct the fire fighters for fast and effective casualty search. There may be a lack of knowledge of the physical environment (e.g. layout of building interiors), and this can also hinder the direction and movement of the fire fighters.

*Proposed technological solution:* The use of networked embedded technologies to distribute and maintain the transmission of data acquired from personal location sensors and virtual map of the physical environment during system damaging scenarios.

*Usability (operational) aspect:* Impacting on operational goals of life preservation (both from a fire fighter and potential victim perspective). Potential for increased operation effectiveness.

*Stakeholder feedback:* The fire commanders highlighted the need to (either personally or via someone else) control the search for people by being able to direct the movement of the fire fighters. An example would be where there are multiple teams in an incident (each with a team leader) - it is useful to be able to remotely direct them into different rooms/sectors by giving them direct navigation instructions. At the moment, fire fighter locations are determined by reference to fixed locations (eg cross passages in tunnels). The locating of firefighters is particularly problematic in large, complex and/or relatively undifferentiated environments such as cargo ships. A potential drawback is the accompanying need for accurate electronic maps of the incident showing escape routes and fixed and dynamic hazards. The most effective solution would be a sensor network that would enhance electronic maps by identifying/locating all potential victims within an incident. The fire fighters could then be actively directed towards them, whilst taking into account the physical layout of the incident.

***Opportunity #4 Accounting for vehicle occupants***

*Problem summary:* It can be difficult for tunnel operators to determine how many occupants are in cars at the scene of an accident, and keep track of them if they start leaving their vehicles. This is particularly the case when smoke obscures CCTV images.

*Proposed technological solution:* Tagging technologies to identify and track the number of vehicle occupants and determine whether they have remained in the vehicle or have evacuated. The use of networked embedded technologies to distribute and maintain the transmission of data acquired from personal and vehicle location sensors during system damaging scenarios.

*Usability (operational) aspect:* To impact on early stage situation assessment and casualty search.

*Stakeholder feedback:* In normal situations, affected tunnels would be evacuated before the fire services arrive. This type of sensing capability would add value in serious situations, but would be of less value during more routine incidents.

***Opportunity #5 Monitoring the integrity of the tunnel infrastructure***

*Problem summary:* The lack of real-time information on the structural integrity of the tunnel infrastructure during a fire in tunnel scenario. This could lead to a lack of confidence regarding the safety of those (casualties and rescuers) during a fire.

*Proposed technological solution:* The use of embedded networked technologies to distribute and maintain the transmission of data acquired from temperature sensors embedded in the tunnel infrastructure during system damaging scenarios.

*Usability (operational) aspect:* Impacting on operational goals of life preservation (safety of all those within the tunnel) and preservation of property.

*Stakeholder feedback:* Both the fire commanders and health and safety professionals described the problems associated with monitoring the structural integrity of tunnels, particularly 'iron pipe' tunnels. However, the fire cladding within tunnels will typically ensure resistance to temperatures in excess of 1000° for several hours. A potential concern is the cost and maintenance implications for a technology that may never be used.

***Opportunity #6 Transmission of information to the fire crew during approach to an incident***

*Problem summary:* The lack of information by the fire service during the early phase of an incident.

*Proposed technological solution:* The use of embedded networked technologies to distribute and maintain the transmission of data acquired from multiple sources. This can enhance the information environment by broadening the data distribution to the fire crews as they are approaching the incident.

*Usability (operational) aspect:* This may enable a quicker and more accurate situation assessment during the early phase of an incident.

*Stakeholder feedback:* A typical quote from a local fire commander was that on the way to an incident 'often we don't know enough …… we will always like to know more'. In theory, sending information to the fire crews (and in particular the fire commander) is useful, but mobile communications between the multiple agencies involved, and mobile data terminals generally provide sufficient information. The usefulness of this capability also depends on the duration of the journey to the incident – in many cases the local responders are situated less than five minutes away, and this limited time window reduces the potential impact of pre-arrival information.

## Results – *challenges* for advanced sensor networks

### *Challenge #1 Introduction of new sensors into the fire in tunnel scene*

*Problem summary:* There is a lack of information during a fire in tunnel incident. There is a need to supplement the existing information environment with sensor data, when the existing information environment is too scarce to enable situation assessment and effective decision making.

*Proposed technological solution:* The introduction of new assets such as sensors and sensor gateways to the scene. This could be by manual (eg distribution by hand) or by automatic means (eg self-directed robots who can optimise their position to restore connectivity). These additional assets are then integrated into existing networks.

*Usability (operational) aspect:* This may impact on the ability to perform a situation assessment when there is scarce information during a fire in tunnel.

*Stakeholder feedback:* There was a combination of interest and scepticism regarding this concept. One fire commander was highly sceptical about this (and other very technological solutions). There were two main issues. He did not necessarily see a need, as much information can be gained through visual inspection at the scene. However this would depend on the incident, and also the degree to which the commander was operating near to the incident – operational practice varied between countries. There was also concern about the reliability and maintenance costs of for advanced devices based on seeing little return for current technologies that they have available (eg infrared helmets and a rapid response motorbike). In contrast, another fire commander was more positive towards new technological solutions, and could appreciate the potential benefits of introducing new sensors within an incident. There was a general concern over the reliability of new equipment, and the impact of having to carry and deploy additional gear.

The tunnel operators were concerned about the overhead costs of introducing additional sensors within an environment. From the operator's perspective a sensor network to supplement the existing CCTV network increases the likelihood of false alarms and represent a substantial maintenance overhead while providing little perceived added value in terms of incident detection and response. However, when CCTV is rendered inoperable through the presence of smoke, the added value provided by heat and smoke sensors will be far greater.

### *Challenge #2 Data transmission to/from/between fire fighters*

*Problem summary:* An inability to transfer data to/from/between individual fire fighters at scene.

*Proposed technological solution:* The use of networking technologies to distribute and maintain the transmission of communications data acquired from multiple sources. System optimisation (eg reduction of sensor data reporting frequency to increase bandwidth available) within an ad hoc and heterogeneous network.

*Usability (operational) aspect:* This may impact on the operational capability and safety of the fire fighters, by increasing communication between them.

*Stakeholder feedback:* There was mixed response to this from the fire commanders. The fire fighters are usually focussed on carrying out specific tasks. They are directed by team leaders, who have been set objectives by the fire commander. [As an example of the different roles, the fire commander will make decisions based on strategic goals and use of resources (eg the decision to employ all resources to focus on containment). They will issue commands to the team leaders based on what they want achieved. The team leader will then instruct the fire fighters to carry out the actions to achieve the goals set by the commander.] There is a rigid hierarchical command and control structure, and hence little need to transfer data between individual fire fighters. However the necessity of continual interaction between team members when working in hazardous conditions was emphasised. This communication would be to determine the well being of other team members rather than to communicate commands. At present this communication will be face to face and/or by radio.

### Challenge #3 Status monitoring of the fire fighters

*Problem summary:* Lack of ability to monitor fire fighter health and operational capability during an incident.

*Proposed technological solution:* The use of networking technologies to distribute and maintain the transmission of mobile and biometric sensor information. This sensor data can include the data used to determine heat stress - eg core body and skin temperature and heart rate (McLellan and Selkirk, 2004) - and reserve capacity within breathing apparatus.

*Usability (operational) aspect:* This potentially impacts on the operational capability of the fire fighter, but is particularly relevant to the maintenance of the safety of the fire crew.

*Stakeholder feedback:* The fire commanders were negative towards the health monitoring idea for two reasons. They felt strongly that the individual fire fighters were able to assess their own capability to operate within a given environment – they have personal responsibility for this, and this should not be removed from them. In addition, the operational capability of an individual fire fighter would depend on a number of personal and contextual factors including whether the fire fighter was simply having an 'off day'. A fire fighter can judge how these factors combine to impact on their capability at any point in time ('how they feel'). Embedded sensors (eg heart rate and temperature) would not capture the subtleties, and would result in false negatives and false positives. Automatic registering of fire fighters as they entered a incident, plus a more accurate means of tracking the rate of air usage with breathing apparatus was however welcomed. At present this is usually done using white boards, markers and tags. A robust sensor network could log fire fighters in and out of an incident, and provide a more accurate forward projection of reserve air capacities.

## Discussion and conclusion

The above section has described a number of opportunities for advanced sensor networks to impact on a fire in tunnel situation. It has also described concepts which offer theoretical benefit, but in practice pose challenges to successful introduction. In reality, there are opportunities and challenges associated with each of the ideas outlined above.

Taking a user-centred perspective it is clear that advanced sensor networks have considerable potential for enriching a scarce and degrading information environment as would occur in a fire in tunnel incident. New display technologies such as head mounted displays or other portable interfaces rely on a robust underlying network infrastructure that can deliver information as and when needed – the 'right information, at the right time and in the right way' referred to by Hollnagel (1988). [However, as discussed by Flach et. (1998), the fundamental question is actually that of defining 'right' within any given context.]

In some cases, subtle design of proposed technologies can differentiate between potential success and failure. For example, although a proposed 'health monitoring' function may seem to offer theoretical benefit to fire fighters, the concept behind this was incompatible with the self-reliance values of the fire fighters. However, a redesign so it is a 'self help' rather than 'remote monitoring' aid may be more successful.

There are a number of themes which emerge which are pointers to how the technical capabilities described may be harnessed successfully for stakeholder benefit:

- The need to explicitly add value over and above existing safety features (eg the use of CCTV to identify incidents)
- Compatibility with organisational structures (eg the existing hierarchical nature of command and control)
- Consistency with the values of individual stakeholders (eg the self-reliance of fire fighters)
- The trade off of technical constraints (eg bandwidth and battery life)
- Graceful degradation during failure and traceability of data
- Robustness of solutions
- Concepts based on assisting the stakeholder rather than unnecessary automation (Bainbridge, 1987)

The most effective technologies may be those were there are benefits to multiple stakeholders and where technologies can be incorporated into working practices without imposing additional demands on stakeholders.

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