Sensing Danger - Challenges in Supporting Health and Safety Compliance in the Field

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Abstract

Many workers operate in environments that are inherently hazardous and that are subject to strict health and safety rules and regulations. We envisage a world in which physical work artefacts such as tools, are augmented with intelligent mobile nodes that are able to observe the working activities taking place, evaluate compliance with health and safety regulations and assist or actively enforce compliance with these regulations. This vision creates a new field of work in the area of health and safety aware intelligent mobile sensor networks. In this paper we describe a number of new challenges faced when developing mobile systems for compliance with health and safety regulations.

1. Introduction

Workplace health and safety is an important societal goal that concerns businesses and governments alike. In particular, industrial areas such as construction sites, factories and chemical plants, pose enormous risk for workers and operatives. To ensure health and safety, work practices are governed by extensive rules and regulations, and compliance with these regulations is a major issue for employers. As complexity of legal requirements mounts, companies are forced to devise innovative ways to ensure health and safety of their employees and compliance with ever changing regulations.

Sensor-based mobile technologies provide opportunities for creating novel health and safety solutions for industrial workplaces. Together with several industrial companies we are exploring concepts and technologies for assisting workers in the field through automatic real-time assessment of work activities. Our approach is based on the idea of turning work-related artefacts such as tools and equipment, into cooperating mobile computing entities able to recognise, track and assess work activities, and to provide real-time information about health and safety compliance to workers.

We achieve this by embedding wireless sensor/actuator devices that communicate over ad-hoc wireless networks, into tools. Figure 1 illustrates this concept. Tools equipped with sensors detect ongoing work activities and create activity records. These records are automatically mapped against regulations to assess health and safety compliance. Compliance data is then used to assist workers in the field, for example by providing real-time information about rule violations. Health and safety rules are encoded and stored in mobile nodes, thus enabling full operation wherever and whenever workers operate equipment.

Our approach contrasts sharply with the current practice of health and safety assessment. Although mobile solutions for manually capturing compliance data in the field exist, our field studies at several industrial sites indicate systemic problems related to the completeness, accuracy and consistency of captured data. Our vision creates a new field of work in the area of mobile computing with the introduction of support for health and safety.

We believe that given the humanitarian and commercial benefits, this field is likely to emerge as a hot topic of research for the mobile computing community. In the remainder of this paper we focus on the research challenges for the mobile computing community that arise from such a vision.

2. Understanding Health and Safety Regulations

Health and safety regulations are defined by legal authorities such as governments or international bodies (e.g. Euro-

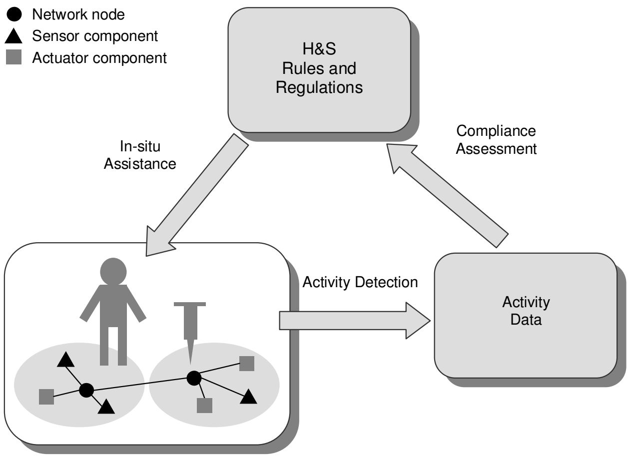

Figure 1. Health and Safety System

pean Union). Typically, these regulations consist of textual descriptions of policies that should be applied to promote safety in the workplace. Such policies may take the form of tasks that need to be performed or dictate limitations in certain aspects of a job. However, one particular characteristic of these regulations is that they do not normally define the specific techniques that need to be employed in order to achieve the goals required. This ambiguity can lead to the acquisition of work practices that may be impractical, unreliable, or that may introduce unreasonable levels of inefficiency.

Currently, most health and safety rules rely on human information gathering and recording in the field with decisions being taken by workers, supervisors or back office staff processing the data 'off-line'. For example, there are certain H&S regulations designed to limit workers' exposure to hand-arm vibrations when operating heavy vibrating machinery. Permitted exposure levels depend on the intensity and frequency as well as exposure time to vibrations. The current practice is for the operatives to manually record tool usage on paper sheets and to estimate vibration exposure by assuming the densest possible surface which results in the highest vibration magnitudes. With the current practice, the problem is, of course, that the ultimate responsibility is left to operatives who might not pay attention to these guidelines or may underestimate the exposure to vibrations.

To understand the domain of H&S support systems we have been working closely with domain experts from major international companies. In collaboration with a large petrochemical company, we have studied the handling and storage of chemicals at a large chemicals plant in UK.

Correct handling and storage of chemicals is critical to ensure protection of the environment and safety in the workplace. For example, hazardous chemicals must be stored in a way that physically separates reactive agents, or storage of certain materials should not exceed a predefined critical mass or volume. However, the manual processes employed are not foolproof, which can lead to accidents sometimes of disastrous proportion.

We developed a prototype system for monitoring H&S compliance consisting of safety-aware chemical containers augmented with intelligent sensor nodes and programmed with domain-specific H&S rules [10]. A container recognises workers' handling operations, assesses its own storage situations and notifies personnel about potential hazards. We developed similar prototypes for H&S compliance checking related to vibration and noise exposure during equipment use.

Through technology probes such as these we were able to identify a number of research challenges faced when developing mobile support systems for compliance with health and safety regulations.

3. Research Challenges

Our vision is of a world in which physical work artefacts are augmented with cooperating mobile nodes featuring both sensors and actuators, and communicating over adhoc wireless networks. For the purposes of this paper we assume a system architecture as pictured in Figure 1.

Collections of mobile sensors, actuators, display units and personal devices form dynamic ad-hoc networks. The data collected by the sensor nodes is used for detecting the activities performed in the field. This activity data is assessed with respect to H&S regulations and any required actions are fed back into the system.

The envisioned H&S infrastructure fulfils a mission critical task and thus must address many of the standard requirements associated with work in such a domain, i.e. it must be reliable, predictable, trusted, fault-tolerant, and manageable. A further challenge for the system we envisage is that it must operate in an environment characterised by change. For example, regulations, sensing infrastructure and the applications operating on the system are all likely to be subject to constant change. The dynamic nature of both regulations and physical infrastructure requires a dynamic and adaptive process for compliance checking.

To address this challenge we are exploring the use of a model-based approach with three elements:

1. a declarative model of H&S regulations
2. a dynamic model of the infrastructure describing its capabilities and the location of its components
3. a top-down approach for compliance checking that dynamically maps compliance tasks to infrastructure assemblies.

Rather than performing sensing and interpretation bottom-up, i.e. driven by available sensor data, we envision a top-down approach that extracts sensing tasks from the regulation model, identifies which parts of the sensing/actuators infrastructure are able to perform which tasks and assigns tasks accordingly. Tasks could be reassigned dynamically as regulations and infrastructure change.

A declarative model of H&S regulations could dramatically reduce the 'time to market' of H&S policies, while a dynamic infrastructure model would allow dynamic optimisations at many layers of the system. Indeed, by determining how to evaluate H&S rules there is the possibility to carry out the processing either locally or remotely (from the perspective of the mobile node). Global loops span from sensors and actuators to backend systems and are appropriate for non-time critical system behaviours. Local loop processing, on the other hand, involves clusters of strongly connected devices in the field able to make decisions about local phenomena. For example, the decision as to whether a storage regulation has been violated in the case study described in Section 2, should be made locally by safety-aware containers.

Developing H&S systems such as the ones described, presents numerous challenges at many different levels of the system. For this paper, we do not describe the traditional challenges associated with developing safety-critical systems but instead focus on novel challenges that arise from trying to support H&S compliance. Many of these challenges reflect the combination of technical and human aspects that we believe will be characteristic of systems in this field and is a factor that differentiates work in this domain from many conventional sensor networks.

3.1. Specifying and Recognising Compliance

The fundamental task of our proposed system is to understand what is going on in the workplace and to match regulations against this understanding. This requires that components of the system are able to build a dynamic world model that includes people, tools and activities, and that regulations can be expressed in terms of (or at least mapped to) objects in this world model.

Constructing and maintaining a model of this type is a complex task that has been the subject of much research. There is a significant amount of work on activity recognition within ubiquitous computing that enables systems to understand the activities being performed by their users. However, the nature of our domain raises new challenges. Recognising activities undertaken by field workers is distinct from conventional ubicomp activity recognition that has traditionally assumed well constrained environments such as smart rooms [11], or wearable activity recognition that has focused on body-worn sensors only [2]. In addition, these approaches assume plentiful training data that enables machine learning techniques to be employed [6].

In our target environments such assumptions do not hold: the environment is dynamic with people, tools and activities changing and sensor nodes arriving and leaving. As a result, activity recognition is significantly more challenging — for example, representative training data is unlikely to be available in a timely fashion.

In addition to creating a world model, it is also necessary to provide a means of specifying H&S rules in terms of this model. H&S rules currently do not provide any of the formalisms required for automation. For example, to enable H&S rules to be specified for our system we require constructs for expressing not just the logic of the rules themselves but also uncertainty and spatial and temporal aspects (e.g. proximity, containment and adjacency). Developing an appropriate model and language for expressing H&S rules is therefore a significant challenge.

3.2. Engineering Optimisations for Health and Safety

The purpose of the envisioned H&S system is not just to collect compliance-related information for off-line analysis. The greatest advantage comes from the ability to warn workers and supervisors in the field about violations of regulations and impending dangers so that they can adjust their work activities accordingly. In effect, an intelligent H&S system can be viewed as a hybrid of an interactive system and a distributed control system.

A significant challenge for this domain resides in the design and development of self optimising network configurations capable of balancing the real-time and energy efficiency requirements of the system. In essence, such networks must be equally capable of supporting a device for months at a time, yet react without delay when a dangerous scenario arises.

Existing self optimisation techniques for ad-hoc networks typically use network topology information along with the power status of nodes to derive packet and sleep schedules to maximise the 'lifetime' of the network [14]. Such approaches would not provide optimal solutions in H&S systems, as they do not take into account two key cross-cutting aspects of the system - human factors and formalised application requirements.

Human Factors. Unlike more traditional wireless sensor networks, humans are an intrinsic part of our system. Humans can respond to warnings or alerts from the devices and interact with them to improve the system itself, e.g. they are capable of repositioning devices in the environment to improve the accuracy of sensed data. The optimisation of such environments needs to take into account the capabilities of not just network nodes, but the humans in the system.

Formalised Application Requirements. Companies tend to translate H&S regulations into company work practices and rules that workers should follow to maintain H&S compliance. Given the formal nature of these policies, the requirements for supporting a certain H&S regulation can be precisely and dynamically derived at execution time by all layers of the system. The networking subsystem in particular can use these requirements to form more accurate optimisation of routing, scheduling and aggregation schemes than can be achieved from topology information alone. The H&S rule sets are naturally distributed in nature, requiring data sensed from different nodes to be compiled together to infer the current activity. Considerable gains in terms of overall network energy efficiency could be achieved by partial execution of rules on the most relevant nodes (e.g. where the sensed data is gathered) - essentially extending the ideas of distributed sensor data aggregation and query processing [3, 5] to include application specific processing.

3.3. Providing Accountability and Data Provenance

For systems that are associated with H&S there is a need to be able to record data and system events for a variety of purposes such as accident investigation, litigation and long-term studies of the impact of working practices. For H&S systems we identify two distinct requirements. Firstly, we need to be able to establish the provenance of data (such as sensor readings) within the system and, secondly, we need to be able to record and replay system events in order to duplicate the behaviour of the system at a given point in time.

Data provenance typically refers to the process of tracing and recording the origins of data and its movement [1]. To date, most of the work on data provenance has been carried out in the Grid and Database communities and assumes a fixed permanently available networking infrastructure and plentiful storage and processing resources. The challenge for systems such as the one we are proposing is to establish data provenance as data is created, e.g. on the nodes attached to physical artefacts and then to maintain this provenance throughout the data item's lifetime despite the limited resources and intermittent communications available.

Maintaining data provenance as the data is moved and modified is a specialised form of an audit trail [9]. Indeed, every piece of data needs to be tagged by all services that alter its contents. More generally, we require the ability to create audit trails of system events to enable us to record and reproduce system behaviour. This is essentially a system logging activity that is complicated by the target operating environment of low power ad-hoc wireless networks.

In addition to the constraints imposed by the operating environment, creating audit trails for H&S systems creates a unique opportunity to correlate system events with the workflows that are an inherent part of many H&S rules. This coupling of audit trails and workflow has been explored in [12]. Audit trails themselves may also be the subject of data provenance enquiries.

We note that both data provenance and audit trails inherently rely on trusted system components. Trust in this context is a complex issue that has several dimensions. Firstly, there is the issue of the extent to which the sensor readings themselves can be trusted - related of course to the issue of uncertainty. A second element of trust relates to the users involved in the system. In sharp contrast to most sensor network research, we have users involved in the activities that we are trying to monitor. Moreover, these users may be motivated to try and distort the sensor readings for a variety of reasons (e.g. to circumvent a specific health and safety regulation). Detecting and preventing deliberate malicious behaviour by users (as opposed to accidental non-compliance) represents a significant challenge for the design of health and safety systems.

3.4. Ensuring User Comprehension and User Acceptance

We see two fundamental human-factor challenges in the design of intelligent H&S systems:

1. how to design intelligent H&S systems to maximise user understanding

2. how to design systems to maximise the chance that they will be accepted by users.

Understanding, i.e. comprehension of the system's capabilities and limitations, is crucial for an effective cooperation between human and intelligent system. In the context of flight control systems, it has been shown that people may over-attribute capabilities to intelligent systems (i.e., mistakenly assuming that because a system can authoritatively automate one aspect of functionality then it can also automate other aspects of functionality) [8]. We do not know if this effect will increase or decrease if we embed computation and intelligence into previously un-augmented artefacts such as drums and drills.

Acceptance of intelligent H&S systems by workers in the field is determined by a number of factors. For example, privacy is likely to play a central role because such systems present possibilities for intensive surveillance. Privacy has been the subject of much research techniques such as anonymising, hashing, cloaking, and blurring [7] that work in personal and social settings. However, it is unlikely that such techniques would be adopted by organisations interested in maximising visibility of work activities.

To address these challenges we see a great potential in approaches aimed at making systems *scrutable*. Scrutability is a term that is used in intelligent user interface research to describe a system that allows a user to inspect the model the system maintains about him [4]. Scrutability has also been used in the context of Bayesian reasoning to help users understand how decisions of a complex interactive system are generated [13].

Scrutability has the potential to increase users' understanding, confidence and trust in a distributed sensing and reasoning system by making the system's assumptions and behaviour transparent while at the same time limiting privacy concerns. We see particular opportunities in exposing high-level provenance data to users and for generating explanations of the system's behaviour that can be understood by users. For example, in the drum scenario from Section 2, the system should not only raise an alarm if drums are stored incorrectly, it should also allow the worker, who is well versed in safety procedures, to ask the system why a particular regulation has been violated. The system's answer might refer to provenance data such as sensed qualities (for example object distances), involved system components and safety regulations to generate a situation dependent explanation.

4. Conclusions

Health and safety compliance is an issue of major importance in modern society. Improving the levels of compliance has the potential to both save lives and bring substantial economic benefits. In this paper we have introduced the topic of mobile H&S systems and presented the results of our domain analysis work. This new field of work raises important challenges that cross-cut multiple system levels from hardware design to user interaction. By addressing these challenges, the mobile computing community will be able to make a significant contribution to the well-being and productivity of workers in hazardous environments.

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