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A wearable system for firefighters smoke exposure monitoring

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Abstract
Firefighters (FF) have to deal in their routine with dangerous situations, exposing themselves to extreme environmental conditions, which can put their lives at risk. Extreme heat exposure, smoke inhalation and reduced visibility are among the most significant hazards to firefighters involved in the suppression of forest fires. In this sense, some new technologies were built addressing the monitoring of firefighters health in the field, mainly sport-oriented solutions adapted for both scientific studies and commercial solutions. However, none of those aim at the mitigation of the main reason for incidents involving firefighters: the exposure to dangerous concentrations of air pollutants.
Our purpose is the development of an integrated hardware and software solution that allows the online monitoring of vital and environmental parameters, helping the FF to preserve their personal health and safety. The system is composed of a specific hardware device attached to the helmet that measures several parameters of interest (e.g. elevation, air temperature, atmospheric pressure, luminosity, exposure to carbon monoxide and nitrogen dioxide), and a mobile application running in a smartphone, which processes information gathered by the helmet hardware to determine if the firefighter is at an acceptable level of exposure/danger and triggers an alarm, if necessary.
From an operational point of view, this work proposes a cost-effective solution to monitor FF smoke exposure in typical adverse scenarios such as forest fires, allowing the detection and mitigation of hypothetical intoxication incidents. The hardware component is easily integrated in standard firefighter's protection equipment and the mobile application can run in any "off-the-shelf" mobile computing device. Beyond the stand-alone firefighters monitoring perspective, this wearable technological solution opens several opportunities as a data source. In this sense, under development is the integration of the near real-time observations into a Decision Support System (DSS) aiming to provide knowledge-based aid to firefighters at critical decision-making situations, thus helping with the safe and successful management of fire fighting.

Keywords*: fire safety; smoke exposure; wearable sensor.*

1. Introduction

Firefighters (FF) have to deal, in their quotidian, with dangerous situations, exposing themselves to extreme environmental conditions, which put their lives at high risk. Extreme heat exposure, smoke inhalation and reduced visibility are among the most significant hazards to firefighters involved in the suppression of forest fires.
In this sense, there are some new technologies that enable the monitoring of some FF health parameters (e.g. heart rate, ventilation frequency, r-r interval) for commercial [Zephyr Technology, 2014] and scientific purposes [Heimburg *et al*., 2006]. However, these technologies are only partial solutions and mostly oriented to the offline analysis of physiological data, not taking into consideration the problem

of aiding the FF in the terrain nor the needed environmental data. Even the commercial solutions are actually adaptations of sport-oriented systems, and are not well suited for realistic operational conditions [Teie, 2005], letting important issues as ergonomic, needed monitoring variables or operational concerns out of their scope.

An illustrative example is the synergy between wearable technologies and mobile computing [Coimbra *et al*., 2012], in which FF were monitored by their own smartphone [Colunas *et al*., 2011] and using wearable sensors [Cunha *et al*., 2010, Cunha, 2012] (see Figure 1). In this previous work, physiological variables were nicely adapted to a wearable system that was specifically developed to FF requirements. Nevertheless, the needed environmental variables were not integrated.

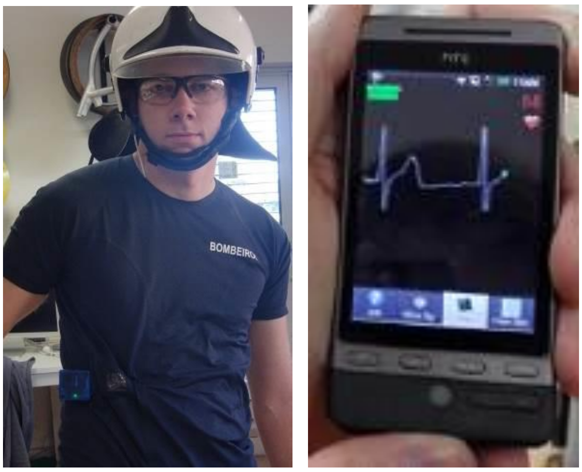

Figure 1. Vital Responder setup: wearable hardware (on the left) and the mobile application (on the right).

Recognising the power of mobile computing devices features (e.g. computational power, wireless networks) using wearable hardware as terrain sensors, our purpose is to contribute for mitigating one of the main reasons for incidents involving firefighters: the exposure to dangerous concentrations of air pollutants [Miranda *et al*., 2012]. The main goal of this research is the development of an integrated hardware and software solution that allows online monitoring of vital and environmental parameters that influence the firefighter's health and safety.

2. System Description

To achieve the referred goal, two technological paradigms were merged: wearable electronics development and mobile programming, as it is depicted in Figure 2.

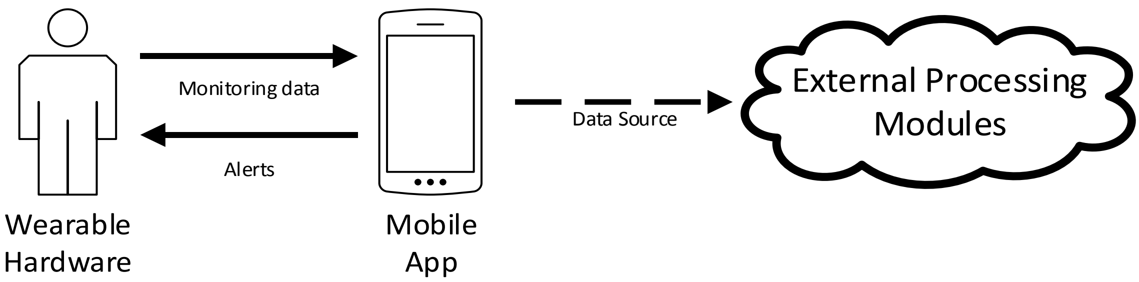

Figure 2. System interaction.

The wearable hardware consists on a sensored helmet unit (Figure 3) to be used by the firefighter. This device allows the measurement of elevation, air temperature, atmospheric pressure, as also the personal exposure to carbon monoxide (CO) and nitrogen dioxide (NO_2). These specific air pollutants are known to cause short term effects (e.g. headache, dizziness, nausea, dyspnea, loss of consciousness) [Treitman *et al*., 1980; Morrow, 1984; Sandstrom *et al*., 1990; Prockop *et al*., 2007] that can put a firefighter's life in immediate danger. In order to allow online processing of these variables, the hardware module transmits the information over a Bluetooth network that can be used by smartphones to receive and process the information.
The mobile application uses the information gathered to determine if the firefighter is at an acceptable level of exposure/danger and triggers an alarm, if necessary. Another potential feature of the mobile App is to add some information (e.g. GPS, fall detectors) to the hardware stream and relay it to some kind of superior monitoring platform over Wi-Fi networks. This information can then be used by the team leader to monitor his crew.

2.1. Hardware Modules

The hardware modules were developed in-house. The development process was based on the requirements identified based on the outcomes from two research projects:

- FUMEXP (PTDC/AMB/66707/2006), with special emphasis on sensors choice for a set of air pollutants of interest and corresponding typical ranges;
- VitalResponder (CMU/PT/CPS/0046/2008), due to the usability concerns and the technological possibilities already assessed.

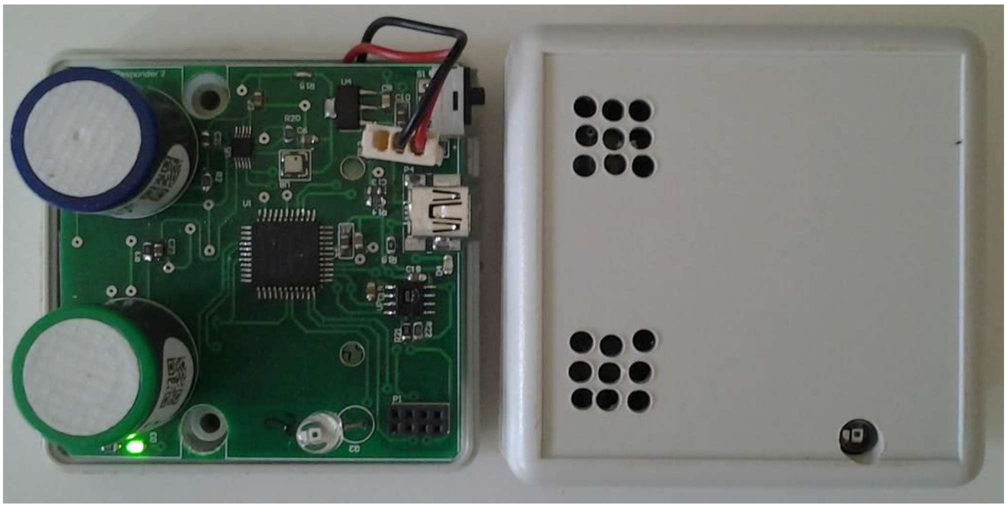

Figure 3. Helmet module prototype: hardware picture (on the left) and its integration on suitable box (on the right).

First of all, a requirement analysis was performed taking into consideration the state of the art on firefighters monitoring systems. It was concluded that the commercial solutions available for the monitoring of human exposure (usually in industrial environments) are not well suited to firefighting operational conditions due to their weight, discomfort and positioning. To mitigate these gaps, and after consulting stakeholders from several fire departments, a hardware device was designed with the objective of being placed on the firefighter’s helmet. This approach presents several advantages, but the most representative are:

- ergonomy: with an approximate weight of just 150 g the device becomes imperceptible to the firefighter that is being monitored;
- proximity to the firefighter airways, allowing accurate measurement of the pollutants inhaled;

- usability: once the helmet is a part of the mandatory protection equipment, firefighters do not have to take extra concerns about the monitoring device;
- endurance: due to the environmental factors surrounding a wildfire scenario, it's very difficult to keep an electronic device working properly. For this reason, attaching the monitoring device on the helmet improves the hardware's safety and accuracy.

However, attaching a monitoring device on a firefighter helmet is not a trivial process due to its ratification standards (e.g. EN 443 for helmets hull, EN 16471 for wildland firefighting helmets). In order to surpass these constraints, an embedded helmet socket (Figure 4. left) was used to attach the monitoring hardware module (Figure 4. right). Originally, this socket was designed to support attachments as flash lights and fulfils the applied standards.

Figure 4. Helmet module prototype integration: original firefighter helmet (on the left) and helmet equipped with monitoring hardware (on the right).

Therefore, in order to build an electronic device small enough to be integrated on a firefighter helmet, we tried to achieve a suitable agreement between the technological possibilities and the most representative environmental variables to measure. Finding support on scientific studies [Ferreira *et al*., 2011], our helmet unit has sensors to monitor the data depicted on Table 1.

Table 1- Environmental data acquired by the Helmet module

Variable	**Units**
NO_2	ppm
CO	ppm
Atmo. Pressure	hPA
Elevation	m
Humidity	%
Temperature	ºC
Luminosity	%

Technologically, we developed a custom printed circuit board to support all the above mentioned sensors and the remaining necessary components:
- electronic front-ends to bridge all sensors with an Analog-to-Digital conversion
- a microcontroller (MCU) unit to gather and process data from all sensors;
- a bluetooth interface, in order to relay data frames processed by the MCU;
- a battery, providing an autonomy of 24 hours, approximately.

CO and NO_2 sensors were calibrated using a calibration gas with a known concentration (100 ppm for CO and 10 ppm for NO_2).

2.2. Mobile application

The mobile application is an evolution of the Android based DroidJacket system [Colunas *et al*., 2011] with support to receive and process data from the helmet unit described on the above section. It can run in an off-the-shelve Android smartphone supporting bluetooth communication, or it can be integrated on a Wi-Fi network and relay data to any connected device.

To extend the DroidJackets physiological monitoring capabilities with the environmental data relayed by the new Helmet Unit we follow the application's original software architecture, replicating the functionalities implemented for VitalJacket®. This approach enables us to maintain all application features (e.g. visualization, persistence, danger alarms, network connection) on an already successful evaluation platform.

More specifically, pairing the smartphone with the Helmet Unit, the smartphone receives, displays (Figure 5), stores and relays all environmental data through a Wi-Fi network, if available.

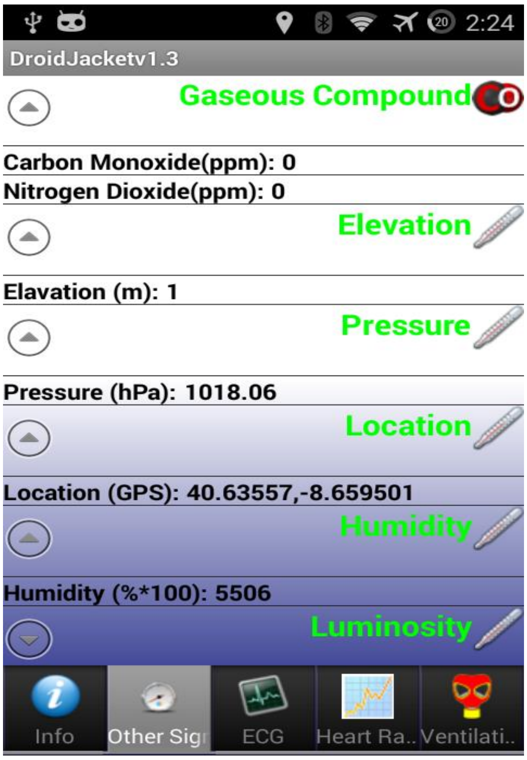

Figure 5 –Improved DroidJacket Version.

Besides the data provided by the Helmet Unit, and other external sensor (e.g. Vital Jacket), the application can use the smartphone's built-in sensors to provide additional information (e.g. GPS, accelerometers, battery).

2.3. Integrability and Scalability

The Hardware setup was built with the aim of integrating new sensors on an effortless manner, enhancing integrability and scalability of the overall solution of the Vital Responder project. In this case, we could integrate the previous physiological wearable platform [Coimbra and Cunha, 2012] with the environmental helmet monitoring unit and a GPS. In that sense, the main challenge was related with the sensors size and form-factor

At the software level, DroidJacket application was used and enhanced. It is an example of scalability, once it has been evolved over several iterations of the project with increasing new features [Marques *et al*. 2013]. At this point, the DroidJacket Android App can gather, in one smartphone, physiological data (ECG, heart rate and actigraphy, from VitalJacket®), environmental data (from Helmet Unit presented above) and GPS location. Furthermore, it enables to add more sensing devices up to the limit of the bluetooth connections (7 channels) or the smartphone processing capabilities.
Under development is an ad-hoc data networking technique that will allow the real-time data acquired in the terrain by several of these wearable monitoring equipments and its bridging to a cloud service that will allow numerical forecast that will enable projections of fire progression, smoke levels and critical exposure, aiming to permit safe and efficient positioning of crews.

2.4. System Evaluation

The whole system will be tested, on a stand-alone mode, during the summer of 2014. We will deploy the system on two fire departments, at two different operational zones. There will be firefighters equipped with our system and all monitored data will be stored on the smartphones, without connectivity between each other. Additionally, we will ask firefighters to produce mission reports to selectively tag relevant events (arrival to fire scene, approach a fire front, etc.) so that all collected data can be analysed for the intended evaluation.

3. Conclusions

Smoke exposure is identified as one of the most important cause of incidents among firefighters. Since the physiological monitoring of firemen has been already addressed, this work signifies one step ahead in this matter, pursuing not only the identification of high risk situations in the terrain, but also contributing to prevent them.
This work proposes a cost-effective solution to monitor firefighters smoke exposure in typical adverse scenarios such as forest fires, allowing the detection and mitigation of hypothetical intoxication incidents. The system is composed of a hardware component easily integrated in standard firefighter protection equipment and a mobile application that can run in any "off-the-shelve" mobile computing device.
Beyond the stand-alone firefighters monitoring perspective, this wearable technological solution opens several opportunities as a data source. In this sense, under development is the integration of the near real-time observations into a Decision Support System (DSS) aiming to provide knowledge-based aid to firefighters at critical decision-making situations, helping with the safe and successful management of fire.

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