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Physiological parameters monitoring of fire-fighters by means of a wearable wireless sensor system

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Abstract. Physiological parameter monitoring may be useful in many different groups of the population, such as infants, elderly people, athletes, soldiers, drivers, fire-fighters, police etc. This can provide a variety of information ranging from health status to operational readiness. In this article, we focus on the case of first responders and specifically fire-fighters. Fire-fighters can benefit from a physiological monitoring system that is used to extract multiple indications such as the present position, the possible life risk level, the stress level etc. This work presents a wearable wireless sensor network node, based on low cost, commercial-off-the-self (COTS) electronic modules, which can be easily attached on a standard fire-fighters’ uniform. Due to the low frequency wired interface between the selected electronic components, the proposed solution can be used as a basis for a textile system where all wired connections will be implemented by means of conductive yarn routing in the textile structure, while some of the standard sensors can be replaced by textile ones. System architecture is described in detail, while indicative samples of acquired signals are also presented.

1. Introduction

Critical infrastructures represent a nation’s material basis for the sustainable welfare of its citizens. Across the world, First Responders (FRs) are called upon every day to protect critical infrastructures against deliberate acts of terrorism, natural disasters, negligence, accidents and malicious behaviour. The occurrence of a crisis (e.g., a fire in a chemical or oil plant, a disastrous earthquake, an incident in a water stemming facility, etc.) requires the presence of a variety of FR teams to restore the situation to a normal (e.g., fire-fighters, civil protection units, police, special forces, etc.)

During the critical phase of a disaster situation, the FRs need to enter a harsh environment to search and rescue human lives, as well as control and mitigate damage. The environment is usually obscured with smoke, noise and rubble, while indoor environments usually pose a risk of collapse or sudden and
life-threatening change of the floor plan. Such situations pose the life of FRs and infrastructure users at risk, making orientation and movement difficult. Abundant threats include fire, explosion, toxic gases, emission of unknown substances, falling objects etc. A worst case scenario could be that of a fire at a chemical plant that also includes offices. Reconnaissance is slow, while environment awareness and awareness of the FR team members’ whereabouts and physiological parameters monitoring are critical. Another scenario could be that of a bomb disposal mission in populated areas: the combination of the protective suit's weight (~ 40 kg), physical activity, high ambient temperatures, and restricted airflow can cause the operative's temperature to rise to dangerous levels during missions, impairing their physical and mental ability [1]. A body sensor network could be used in order to monitor physiological parameters in such conditions. Other approaches may consist in using low processing power and low consumption tags for aggregate collection of physiological data and delivering pertinent information to FRs [2].

Another issue of critical concern is the interoperability of communications platform among diverse teams of FRs [3]. Ubiquitous coverage is a necessity and needs to be provided in a seamless manner. In this context, pervasive technologies, such as Wireless Sensor Networks (WSNs), or technologies regarding the vision and navigation of FRs, can be of great help [4-5].

In this paper, we present early results of a wearable wireless sensor system for the timely acquisition of physiological parameters data of fire-fighters, as a characteristic FRs example. The proposed system comprises of WASN nodes based on components of low frequency wired interface, making it suitable for future implementation using textile electronic components and seamlessly incorporating it to existing fire-fighters uniforms. The communications infrastructure to transmit the data to the local headquarters is based on a WSN that can be deployed on the spot independently from any the existing infrastructure in the operations area, since this might be damaged. In the following paragraphs, the system architecture is described in detail, while indicative samples of acquired signals are presented.

2. Wireless sensor network architecture

The proposed system for the monitoring of the physiological parameters of fire-fighters comprises a typical WSN and is intended for use at the operational level. Specifically, the commander of a team of fire-fighters continuously gets updated information on the health status, stress and fatigue level of the team members and based on this information decides which tasks should be assigned to whom. In this sense, the proposed WSN consists of two kinds of wireless nodes: one central “commander” node and a number of “fire-fighter” sensor nodes. Both kinds of nodes are implemented using the same hardware (HW) devices, but with different functionality. Each one of the monitored fire-fighters carries one “fire-fighter” sensor node. Such nodes are equipped with a number of sensors (cf. section 3) that provide a set of physiological parameters’ measurements. These measurements are wirelessly sent to the central “commander” node and from there to a personal computer or tablet; the “commander” node is a central point that collects all available information and forwards it to the computer where the received data are stored and processed. Of course, the “commander” node is also equipped with sensors. Note that since both kinds of node are identical in terms of HW, in case of
emergency, e.g., if the command authority has to be transferred to another person, the system can be rearranged so that new roles are distributed to the wireless nodes. A block diagram of the proposed WSN is shown in Figure 1.

The short range radio frequency (RF) category includes a broader range of technologies and has become synonymous with Bluetooth, Wi-Fi and ZigBee. However the protocol selected for the specific application was Wi-Fi, mainly for reasons of compatibility with a wide range of personal computers and tablets, which provides flexibility in the procurement of this kind of commercial off-the-self equipment (COTS). However, this choice also provides flexibility for future upgrades of the system, either in the form of an increase of the monitored sensors per sensor node (which would increase the required wireless throughput), or in the form of an upgrade of the processing and display means (computer).

The 802.11 standards, which are widely known with term Wi-Fi, constitute a set of IEEE standards for the creation of wireless local area networks (WLAN) and when initially introduced were destined to expand the wired computer connection (Ethernet) to the wireless area. The 802.11 family contains a series of standards which are: 802.11a, 802.11b, and 802.11g. These standards use the orthogonal frequency division multiplexing method (OFDM) and provide theoretical speeds up to 54Mbps. 802.11a uses the frequency band of 5GHz but does not provide compatibility with the respective network cards used by the other two standards. 802.11b and 802.11g transmit at 2.4GHz and are compatible between them and provide maximum possible speed when communicating between them. Wi-Fi became known in the last years, creating a new method for devices to access the Internet. Table 1 depicts the frequency bands and the theoretical and actual speeds of the various 802.11 standards. [6].

In our application, we use the 802.11 basic services set (BSS). BSS topology is a networking topology in which the wireless network has cluster form. In each cluster there are a number of wireless stations (clients), which communicate between them through a central distributor BS (Base Station), or, more commonly, AP (Access Point). In our case the central “commander” node is the BS [7].

![Figure 1. Wireless sensor network for fire-fighters physiological parameters monitoring.](image-url)
Table 1. The frequency bands of 802.11 standards.

<table>
<thead>
<tr>
<th>Standard</th>
<th>Frequency Band</th>
<th>Typical Transmission Rate</th>
<th>Theoretical Transmission Rate</th>
<th>Range Indoors</th>
</tr>
</thead>
<tbody>
<tr>
<td>802.11a</td>
<td>5GHz</td>
<td>23Mbps</td>
<td>54Mbps</td>
<td>35m</td>
</tr>
<tr>
<td>802.11b</td>
<td>2.4GHz</td>
<td>4.3Mbps</td>
<td>11Mbps</td>
<td>38m</td>
</tr>
<tr>
<td>802.11g</td>
<td>2.4GHz</td>
<td>19Mbps</td>
<td>54Mbps</td>
<td>38m</td>
</tr>
</tbody>
</table>

3. Wearable sensor node

The WSN nodes of the proposed system are an example of wearable electronic system incorporated in the fire-fighter’s suit. Both types of nodes, at this point, carry five kinds of sensors: electrocardiogram (ECG), galvanic skin response, thorax belt sensor, body temperature and tri-axial acceleration sensors for the monitoring of physiological parameters of the firemen, such as heart rate, perspiration, respiration rate, body temperature and motion, respectively.

The wearable sensor node design has been based on the widely spread single-ship control unit Arduino Uno [8]. This is an open source HW and software (SW) platform, providing a low-cost solution, which, on the other hand, provides more than enough processing power and memory for the real-time application of interest. It uses the ATmega328P microcontroller, an Atmel 8-bit RISC processor. It incorporates the following key features: 32KB flash memory, 2KB SRAM, 16MHz clock, 6 channel 10bit analogue to digital converter (ADC) sampling up to 76.9 kSPS, 2-wire serial interface (TWI), and programmable serial interface (USART).

All the sensors used in order to monitor the firemen’s physiological parameters, except from the tri-axial accelerometer, are analogue. This means that their signal is digitized through the available ADC. Tri-axial accelerometer directly produces digital output and uses the TWI, which is a serial interface compatible with the widely employed I2C, to send its measurements to the processor. IEEE 802.11 connectivity is obtained through an XBee Wi-Fi module which communicates with the processor over a serial interface. The structure of a sensor node is depicted in Figure 3 in the form of a block diagram.

Figure 2. Wireless sensor node. Each fire-fighter suit communicates with the central “commander” node via Wi-Fi.
The current implementation is wearable in a limited degree, in the sense that all sensors, printed circuit boards (PCBs) and electrical connections are implemented using conventional low-cost COTS electronic modules which are integrated into the garment using different types of textile hosting structures like pockets, hemming etc. Figure 3 shows the currently employed electronic components of a wearable sensor node.

![Figure 3. Low-cost COTS HW implementation of the “fire-fighter” sensor node.](image)

In the next steps of our project we intend to replace as much as possible of the electronic modules and the sensors of our system with textile structures or electronics that can be easier incorporated to the garment. For example, Arduino Uno can easily be replaced by a flex-PCB on which the same electronic components as in Arduino Uno will be hosted. On the other hand, our intention is to replace all cables, even the transmission lines carrying the RF signal, with conductive yarn routes on the fire-fighter suit [8-11]. Moreover, we intend to replace ECG sensors with textile electrodes, either based on conductive yarns or screen-printed [12,13], while respiration rate, temperature and skin moisture (perspiration) could be monitored using appropriately designed variations of conductive yarn based knitted sensors [14-17]. Finally, even the antenna could be partially or fully textile [18,19]. Of course, a key aspect of successfully integrating these structures into the textile substrate is the main aim of our project: reliable textile welding. The integration will be considered successful if this results, at the same time, to a reliable electronic system and a functional, as well as comfortable, garment.

4. Physiological parameters acquisition
In the following we present some characteristic examples of signals acquired in real-time by the proposed wearable wireless sensor node. Actually, the signals presented in Figures 4 to 6 were acquired by a “fire-fighter” sensor node, wirelessly sent to the central “commander” node and then to a personal computer where they were stored.
Figure 4. Simultaneous monitoring of all analogue sensor signals. From bottom to top panel: ECG, perspiration, respiration and body temperature. All y-scales are normalized in the interval [0,1].

Figure 5. Excerpt of the high sampling rate analogue signals, shown in Figure 4. Bottom panel: ECG, top panel: perspiration. All y-scales are normalized in the interval [0,1].
Figure 6. Excerpt of the tri-axial accelerometer time series. First a jumping up and down and then on the spot jogging are presented. All y-scales are normalized in the interval $[0,1]$.

In the next step, which is still under development, this raw physiological signals information will be used to extract useful information about the health status, stress and fatigue level of the fire-fighters. For example, ECG signal will be used to extract the heart rate, tri-axial accelerometer measurements to extract information about motion condition of the firemen, i.e., if a fireman is not moving for a time period longer than a specific threshold, this might indicate that has lost consciousness and his/her life is in immediate danger. On the other hand, respiration, perspiration and body temperature data will be combined with heart rate data to infer stress and fatigue level.

The main idea is that the commander will have a screen depicting each one of his team members in the form of a light indications column vector. Each line of this column vector will correspond to one specific characteristic of firemen’s condition; a green light at a specific point will mean that he/she is within the normal levels, whereas a red light will indicate that normal levels have been exceeded for the specific characteristic. Nevertheless, further analysis on the processing of the raw sensor data is out of scope of this work.

5. Conclusion
A wireless sensor network based on wearable sensor node for the monitoring of fire-fighters’ physiological parameters has been presented. The current form of the employed wearable wireless sensor node is based on low cost, commercial off-the-self electronic modules, which can easily be attached on a standard fire-fighters’ uniform by means of appropriate textile hosting structures like pockets, hemming etc.. System architecture is described in detail, while indicative samples of acquired signals are also presented.

Our future plans include the elimination of all cables. All wired connections will be implemented by means of conductive yarn routing in the textile structure, which is considered feasible due to the low frequency inter-module communications. Even a short-length transmission line based on conductive yarns can be used for the connection between the Wi-Fi transceiver and the antenna, while
the antenna itself can be printed on flex-PCB or implemented as fully textile. Moreover, some sensors can be replaced by textile ones. Of course a key aspect of such a high degree of integration into the garment is the textile welding, which is the main scope of our project.

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