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Biosensing and Environmental Sensing for Emergency and Protection E-Textiles

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Abstract—**The ProeTEX project introduced for the first time a complete set of smart garments integrating sensors for the physiological and environmental monitoring of emergency operators. These "smart" garments have been deeply tested in emergency-like contexts by professional rescuers, in order to assess real-time acquisition, processing and transmission of data from moving subjects while operating in harsh conditions. Here we report an overview of the main results obtained during field trials performed in 2010 by Italian and French professional firefighters, in specialized training centers, while dressing the ProeTEX prototypes. Results clearly demonstrate the benefit and step forward of such a system in order to monitor and coordinate rescuers even during intervention far away from the emergency headquarter.**

I. Introduction

THANKS to the more recent manufacturing processes and advances in miniaturized technology, sensors, communication systems and electronics have become more and more tiny, less power consuming and portable. These progresses have given rise to a new set of applications based on the integration of electronics even within garments. Smart garments are characterized by wearable networks of sensors with autonomous power supply, local processing units and integrated communication ability [1]. Ultimately these architectures are able to capture real-time information from the body and the surroundings environment of subjects wearing the system.

An unquestionable advantage of smart garments is the possibility of monitoring people in natural contexts without any fixed experimental setup or protocol [2]. Moreover there is no need of specific instrumentations. Because of these advantages, a noticeable amount of funding has been released for research and development in this field; remarkably, the majority of these systems have been focused on sensing platform for health and clinical applications (devoted to the monitoring of subjects with particular diseases), for remote rehabilitation monitoring, sports and military applications [3,4].

Here we present a wearable platform with a different target, which has been conceived on two main ideas [5]:

- the selected application field is that of the first responders, consisting of workers operating in harsh conditions like Civil Protection rescuers and firefighters;
- the integrated approach is at wide spectrum: we want a wearable system capable of detecting not only physiological parameters, but also environmental and activity-related variables; a full overview of the emergency operator's status in any condition is needed (even when operator is far away from the coordination site of the intervention).

According to these constraints, a 4-years project, called ProeTEX (Protection e-Textiles: MicroNanoStructured fibre systems for emergency-disaster wear), was funded by the European Community in 2006. ProeTEX ended in 2010 and produced a set of prototypes based on 3 wearable components or garments: a T-Shirt (called Inner Garment and directly in contact with the operator/wearer's skin), an external jacket (called Outer Garment) and a pair of boots. These three components integrate wired and wireless sensors, a central processing unit collecting the sensors' data and a wireless communication module to transmit the information out of the operative areas [5]; sensor-by-sensor distributed intelligence and remote monitoring software allow local processing of the raw data sensors and transmission of relevant parameter's features only. The set of prototypes adapts to the demands of different end-users within the project consortium (Italian and French Civil Protection Dept., firefighters Brigade of Paris, etc.), in terms of type of integrated sensors and textile composition of garments [6].

During the project, a continuous process of testing, end-users feedback and specifications' updating resulted in insightful debugging and improvements of the software and hardware components of the prototypes. In this work we refer to the final phase of this process and, in particular, to a set of field trials performed in 2010 with the final version of the firefighter prototype release: the paper is structured with a brief description of the sensors' architecture and a demonstration of the efficacy and functionality of the system during the aforementioned tests.

II. Wearable Sensors Hosted in the Protective Garment

The final ProeTEX prototype for firefighters is a full set of protective garments composed by a fireproof jacket (based on the one currently employed by the French firefighters brigades), a T-shirt made of fire-retardant fabrics (i.e. Nomex® from DuPont) and a pair of boots (custom

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developed by Diadora within the consortium and already compliant with the EU standards on protective footwear). The garments host a network of portable and wearable sensors that enables real-time and simultaneous detection of physiological, activity-related and environmental variables: an RS-485 serial sub-network connects the sensors placed on each garment; wireless connections between sub-networks, based on IEEE 802.15.4 low power BAN protocol, are foreseen to improve wearableness and operator's setup procedure.

A. Physiological sensors

First responders are often submitted to intense physiological stress conditions, caused by the external environments and by the need of performing extended periods of very intense physical activities. Several studies demonstrated that sudden cardio-pulmonary collapses represent the main cause of death of firefighters during their working activity [7]: therefore the ProeTEX consortium investigated the use of several technologies in order to constantly monitor the most important vital signs of the operators.

Heart Rate (HR): an ECG lead is measured by means of two large (6x3 cm) textile electrodes embedded in the internal region of the Inner Garment, in contact with the skin at thorax level. Electrodes are realized with stainless steel conductive filaments, combined with cotton and Elité and embedded in garment fabric structure during the manufacture process. Electrodes' structure and garment's elasticity in the thorax region were designed to maximize skin-electrode adhesion even in presence of intense physical activity and perspiration [8]. The ECG signal is processed by an electronic unit, within an elastic band worn by the subject, in order to extract the HR.

Breathing Rate (BR): a piezo-electric PVDF transducer surrounds subject's chest, in order to measure the mechanical forces produced during the breathing activity. A customized wearable electronic module processes the analog signal generated by the transducer and extracts its fundamental frequency, which represents a good estimator of the current BR [9].

Body Temperature (BT): measuring internal body temperature is of major importance in order to estimate the physiological condition of a subject. Fast increase of this variable or too high values (>39.5°C) imply the risk of subject's collapse. However, its detection is highly invasive and hardly realizable in scenarios as the ones addressed by ProeTEX. For this reason, large attention was paid to the development of a sensor that enables to approximate the core temperature by means of a measurement at skin level: a commercial thermistor (by BetaTHERM®) is integrated in the internal side of the T-shirt, at armpit level; a neoprene insulating patch (5x6x0.7 cm) is placed over the sensor, to mitigate the environmental radiation's effect [10].

Dehydration (DE): the T-Shirt hosts a wearable electro-chemical dehydration sensor too; it is composed by ion sensitive electrodes integrated into the fabric substrate, and a portable electronic board [11]. Electrodes measure the sodium concentration in sweat, which is strictly related to the operator's dehydration level. The analog signal output of the transducer is processed by the portable electronic board to compensate the effect of the temperature on the signal, to perform A/D conversion and to transform the recorded voltage into a ion concentration signal.

B. Subject's position, activity and posture detection

Remote monitoring of subject absolute position, posture and activity (e.g. falls to the ground, extended periods of immobility) are other imperative aspects of rescuers' surveillance: therefore several technologies were investigated and integrated within the prototypes.

Accelerometers: the large market availability of robust, small, low power and low cost MEMS sensors allows their use in demanding applications, as the ones addressed by the ProeTEX project; two sensors were integrated in the jacket, at collar (CA) and wrist level (WA). Portable electronic modules perform a real-time processing of the signals of the two sensors, in order to extract indexes regarding user's posture, activity/inactivity and falls to the ground [12]. Preliminary researches were carried out on integrating CA signals and physiological data to classify activities and recognize dangerous conditions [13].

GPS module: the use of commercial GPS modules in consumer applications (mobile phones, wristwatches and similar) is largely consolidated. A low cost LEA-5H GPS module (by U-BLOX AG, Switzerland) was integrated in the jacket: its output (standard NMEA strings, updated every second) is used in order to determine user's position and to estimate the subject's walking and running speed.

Organic Field Effect Transistor (OFET) based activity sensor. OFET technology was used to manufacture a deformation/pressure sensor, integrated in the boot, in order to detect the contact pressure between the foot and the ground. The processing of this sensor's signal allows detecting higher-level of information (walking activity, step frequency, lying down posture) [14].

C. Environmental sensors

Besides providing real time measures of the vital signs and activity related parameters of the rescuer, it is important to keep monitored the surrounding environment. The ProeTEX prototypes include four sensors to measure the thermal parameters and toxic gases concentrations.

External Temperature (ET) and Heath Flux (HF) through the protective garment. The high thermal impedance of firefighter's garments protects them from the exposition to sources of heat and flames; unfortunately it does not allow users to feel the outside temperature, so sudden garment burning may occur without any forewarning for the operator. ProeTEX consortium faced this issue by placing two Pt9000 platinum sensors (by Atexis®) in the external layer of the jacket, to measure the air temperature; the sensors' position, on the two shoulders, was selected to detect the higher temperature felt by the firefighter, since the shoulders are the most exposed regions of the body when facing fire; these sensors' outputs are also compared real-time with measures of identical sensors placed within the internal layer of the jacket; once it is known the thermal impedance of garment's fireproof layer, then the two measures' difference provides a good estimation of the HF passing through the jacket [15].

Carbon Monoxide (CO) concentration: CO is an odourless and colourless extremely toxic gas, with density comparable to the air; a small CO sensor, based on electrochemical detection method (CO-D4 by Alphasense), was integrated in the protective jackets. The sensor is placed in the lapel, close to the user's mouth and nose; it is integrated in the outer shell layer of the garment and protected by waterproof gas permeable coating. An electronic module converts incoming voltages into gas concentrations and generates alarm signals in case of detection of values higher than 100 ppm [16].

Carbon Dioxide (CO_2) concentration: another eso-chemical sensor is used to measure the CO_2 concentration around the user (CO_2-D1 sensor by Alphasense). Since CO_2 is heavier than air and accumulates at ground, the sensor is placed in a boot's upper part within a specific housing to be in contact with the air. Similarly to the CO module, the CO_2 one is connected to an electronic board converting the input voltage into gas concentration and generating alarms when it overcomes previously set thresholds.

TABLE I
SUMMARY OF THE RESULTS ACHIEVED IN THE FIELD TRIALS SESSIONS

Sensor	N. tests	N. failures	Major issues
HR	20	3	abnormal oscillations after long use (>20 min) or presence of very intense physical activity (running); robustness of connections between textile electrodes and data processing electronics
BR	20	0	signal quality with subjects crouched or lying down
BT	20	0	several minutes required to get a steady value when the garment is worn
DE	3	0	the sensor produces reasonable values for few minutes only
CA	20	2	slight sensor's displacements in presence of very intense movements.
GPS	17	0	accuracy decreases when user is near high obstacles; positioning is lost when user is indoor
WA, ET, HF, CO	20	0	no remark

III. PROTOTYPE ASSESSMENT

In order to demonstrate prototypes' reliability and accuracy, the ProeTEX consortium carried out intense validation campaigns, including single sensor tests in laboratory conditions and field trials with real end-users, while performing simulated interventions in harsh environments, according to their current working standards.

The first category of tests focused on the physiological (HR, BR and BT) monitoring sensors' assessment. They were carried out in a military medical centre in Grenoble, France; more than 20 hours of data were recorded on 6 healthy and trained adult subjects performing physical activities in a climatic chamber at 20°C, 35°C and 45°C.

Experimental protocols were arranged with medical personnel specialized in the functional assessment of physiological behavior in extreme environments. Signals produced by ProeTEX and wearable sensors were compared with the output of reference *gold standard* devices: a Kontron Supermon 7210 ECG monitoring device, a

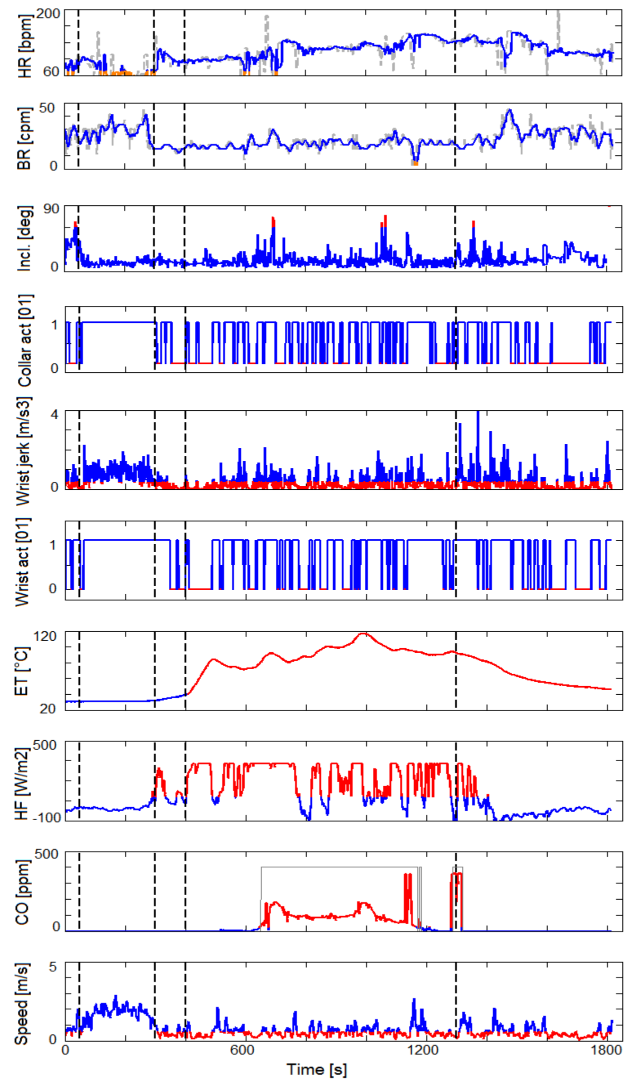

Fig. 1. Time plot of the ProeTEX sensors during one field-trial

spirometer part of the HS 255N Human Physiology Kit by CB Sciences Inc. and a Tempaset Rectal Probe were used to monitor the HR, BR and BT respectively. The performance assessment was based on the computation, for each stage of each acquisition, of the average error and the average percentage error made by the wearable devices with respect to the references. Briefly, the results of these tests showed the reliability of the cardio-pulmonary monitoring systems, even when employed for extended periods (more than 1 h) in mild environment (20°C to 35°C), and up to 30 min of use in a very harsh environment (45°C) [17]. After stabilization periods shorter than 22 min, the BT sensor generated errors lower than 0.5°C with respect to reference rectal temperature measurements; an effect of the external environment was noticed during long exposition (>30 min) at 45°C only.

Once completed the laboratory validation campaign, the prototypes were employed in 2 field trial's sessions, carried out with professional firefighters belonging to the Italian National Firefighter Corp, at the *APT Centre* of Bornasco (Italy), and with professional firefighters belonging to the *Brigade de Sapeurs Pompiers de Paris* (BSPP), at their training centre in Saint Denis (France). During these tests, the recruited operators carried out simulated interventions according to their standard practices, with experimenters interfered as little as possible with their activity. Each session was composed by four interventions, whose difficulty and intensity ranged between walking for about 10 min carrying a weight of 36 Kg, up to performing 15 min of intense physical training, immediately followed by a route inside a chamber filled with smoke at an environmental temperature of about 60°C. Each intervention was executed by three and two users during the APT and BSPP tests respectively: thus 20 tests were executed; tests involved 13 firefighters and more than 6 h of data were acquired.

Differently from laboratory tests, field tests do not allow equipping the users with reference instrumentation: therefore, the goal of these trials was to verify the system's reliability in real harsh conditions, and to demonstrate its efficacy in monitoring the status of a remote operator, rather than to quantify each sensor's accuracy. Given the harsh conditions of use, only the most mature technologies developed by the consortium were used during these tests.

Table I summarizes the main results achieved during the field trials, in terms of reliability issues or manifest failures for each sensor. Figure 1 shows a time plot of the ProeTEX sensor's during one test, composed as follows (each phase is marked with vertical dashed line in the graphs):

- *subject dressed his equipment*
- *subject walked towards the intervention area*: walking speed is clearly recorded by GPS sensor and activity period are detected by the two accelerometers;
- *subject was resting near the entrance of a metallic container*, where the fire was previously set up; an ET increase was measured by the sensor and, earlier, by the HF one (pointing out a fast increase of the difference of temperature between the internal and external side of the jacket's fireproof layer);
- *firefighting activity*: the operators were required to stay in front of the container, near the fire: a clear increase of the ET was detected (up to 120°C); oscillations of the HF signal corresponded to users' changes of the jacket's side exposed to the fire; subject's HR grow up from about 70 bpm to up to 165 bpm, because of the heat stress and extended intensity of physical activity; peaks in the body inclination signal matched periods when the user was crouched in front of the fire; after some minutes of fire exposition, the CO sensor pointed out the presence of toxic gas in concentrations higher than 100 ppm;
- *subject moving away from the fire* and resting.

In general, the wearable electronic system demonstrated to be robust and reliable in all tested scenarios. However the most innovative sensors suffered some failures, especially during tests requiring the harshest condition or very intense physical activities.

IV. Conclusion

This paper provides an overview of the wearable technologies integrated within protective garments designed for firefighters and first responders by the ProeTEX project consortium. These garments host both market available sensors, and newly developed sensors based on textile and wearable technologies. The garments have been intensively tested in specialized laboratories (to quantify the accuracy of each sensor by comparing their outputs with the ones of *gold standard* instrumentation), and "in the field", even in very harsh environmental conditions. The system demonstrated to be enough reliable and robust to be employed in real operative scenarios.

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