Smart Garments for Emergency Operators: the ProeTEX Project

D. Curone, E. L. Secco, A. Tognetti, G. Loriga, G. Dudnik, M. Risatti, R. Whyte, A. Bonfiglio, G. Magenes, *Member, IEEE*

***Abstract*—Financed by the European Commission, a consortium of 23 European partners, consisting of universities, research institutions, industries and organizations operating in the field of emergency management, is developing a new generation of "smart" garments for emergency-disaster personnel. Garments integrate newly developed wearable and textile solutions as like as commercial portable sensors and devices, in order to continuously monitor risks endangering rescuers' lives. The system enables detection of health state parameters of the users (heart rate, breathing rate, body temperature, blood oxygen saturation, position, activity and posture) and environmental variables (external temperature, presence of toxic gases and heat flux passing through the garments), to process data and remotely transmit useful information to the operation manager.**

The European Integrated Project, called ProeTEX (Protection e-Textiles: Micro-Nano-Structured fiber systems for Emergency-Disaster Wear) started on February, 2006 and will end on July, 2010. During this 4.5 years period, three subsequent generations of sensorized garments are being released. This article proposes an overview of the project and gives a description of the second generation prototypes, delivered at the end of 2008.

***Index Terms*—Smart textile, wearable electronics, multi-sensors system, physiological and environmental monitoring**

I. Introduction

In recent years an increasing awareness raised among civil authorities about facing emergencies which involve high number of civilians in wide populated areas. In scenarios like large fires, earthquakes, floods, terrorist incidents or large industrial accidents, professional rescuers must operate maximizing efficacy whilst minimising their own risks. The increasing emphasis raising from recent catastrophic events resulted in political support to provide emergency personnel with advanced support capabilities to continuously monitor and coordinate their activities [1]. In these scenarios the emerging branch of wearable electronics [2], [3], together with advances in information and communication technologies (ICT) [4], can play a primary role. It is now possible to develop information infrastructures fully integrated into garments that collect, process, store and transmit information about the wearer [5], [6] and about the surrounding environment.

Many wearable technologies were developed in the last decade for applications in medical field, in order to extend health and physiological monitoring capabilities typical of the hospitals to the houses of chronic patients [7] or of elderly people requiring continuous surveillance. Currently, a noticeable effort is focused on the application of these emerging technologies to the monitoring of workers during their daily activities, in particular in the case of soldiers or civilian emergency operators performing dangerous activities in wide operative areas in which they can not be directly monitored. Major projects are being carried out both in Europe and in the United States, and involve both academic researchers and industrial companies. One of the forerunner projects in this field was the Georgia Tech Wearable Motherboard [8], funded by the US Department of Navy in the late Nineties with the purpose of developing a shirt allowing to monitor vital signs of soldiers in the battlefield, as like as to detect possible penetration of projectiles. Results of this project constituted the basis for the Future Force Warrior Programme, currently carried out by the US Army Natick Soldier Research, Development and Engineering Centre [9] and aimed at developing active protective clothing for soldiers.

Concerning the surveillance of civil emergency operators, some interesting applications are represented by the sensorized jackets for fire-fighters developed by the Danish companies Viking Life-Saving Equipment A/S [10] and Systematic Software Engineering A/S [11]: the former allows to detect potentially critical heat levels for the wearer by means of temperature sensors integrated in its internal and external textile layers, the latter integrates sensors for physiological state monitoring (heart rate, body temperature and activity detection sensors) as like as for equipment monitoring (oxygen level in tanks) and rescuer location. In the last decade, the European Commission identified this emerging research branch as a major topic in the ICT field, funding projects under the Fifth

Manuscript received June 30, 2009. This work is supported by the European Community Framework Programme VI, IST Programme, Contract n. 26987.

G. Magenes (corresponding author) is with European Centre for Training and Research in Earthquake Engineering - Eucentre and Dept. of Computer Engineering and Systems Science - DIS, University of Pavia, Italy (phone +390382985515; fax+390382985373; e-mail giovanni.magenes@eucentre.it). D. Curone and E.L. Secco are with Eucentre (davide.curone@eucentre.it, emanuele.secco@eucentre.it). A. Tognetti is with Centro E. Piaggio, University of Pisa, Italy (a.tognetti@centropiaggio.unipi.it). G. Loriga was with SMARTEX, Pisa, Italy, now is with D'Appolonia, Genova, Italy (gianni.loriga@dappolonia.it). G. Dudnik is with Csem, Neuchatel, Switzerland (gabriela.dudnik@csem.ch). M. Risatti is with Diadora, Caerano San Marco, Italy (michele.risatti@diadora.it). R. Whyte is with Zarlink Semiconductor Inc, Caldicot, UK (Rhys.Waite@Zarlink.Com). A. Bonfiglio is with CNR-INFM and Dept. of Electrical and Electronic Engineering, University of Cagliari, Italy (annalisa@diee.unica.it).

and Sixth Framework Programmes [12], both for application of wearable electronics in medical field [7] and in workers surveillance and monitoring. Integrated projects such as WearIT@work and ProeTEX belong to this latter research topic. WearIT@work is aimed at developing solutions based on wearable computing technologies to support the workers during their daily activities [13], particularly focusing on four application scenarios: healthcare, aircraft maintenance, production management and emergency rescue. In this latter context the project is going to develop solutions for improving localization of the fire-fighters during their interventions (even when inside buildings or in obstructed environments) as like as communication among the operators and between the operators and the command post coordinating their activities [14].

Concurrently, the European integrated project ProeTEX [15] is focused on the design of a set of functional “smart” protective garments incorporating sensors, communication, processing and power management devices, directly integrated into textiles and specifically designed for emergency/disaster intervention personnel such as fire-fighters and Civil Protection rescuers. The sensorized garments are based both on commercially available technologies suitable for direct integration into clothing (MEMS sensors or low-power micro-controllers) and on newly developed textile and fiber-based sensors, realized within the project. ProeTEX started in February, 2006 and it is being carried out by a consortium of 23 partners from 8 European Countries (see [16] and Table I). The project roadmap foresees the development of three subsequent generations of garments, characterized by a higher and higher level of integration of technological components into textiles. An evaluation of the needs, requirements and specifications of the end-users is done before each generation of prototypes is designed. Once a prototype is released, intense tests sessions are carried out by industrial partners together with the end-users, in order to assess the reliability of each component and of the whole system: results of these trials are used in the development of the next generation. Following this approach, a first generation of garments was released 18 months after the beginning of the project (July, 2007), a second set of prototypes was developed and released at the end of 2008, and an ultimate set of garments will be completed by January, 2010.

This paper mainly focuses on the second generation of prototypes, now representing the state of the art of the project. The following sections are devoted to a description of the main activities carried out for the development of the prototypes: definition of the needs and requirements, prototypes realization and validation tests. The last section is finally dedicated to the future developments foreseen in the next year.

TABLE I
THE PROETEX PROJECT PARTNERS

N	Partner	Acronym	Country
1	National Institute of Physics Matter CNR	INFM	Italy
2	Technical University of Lodz	UNILODS	Poland
3	University of Ghent	UNIGENT	Belgium
4	Smartex S.r.l.	SMARTEX	Italy
5	Milior S.p.a.	MILIOR	Italy
6	Sofileta S.p.a.	SOFILETA	France
7	Thuasne France	THUASNE	France
8	University of Pisa	UNIPI	Italy
9	Dublin City University	DCU	Ireland
10	Commissariat a l’Energie Atomique	CEA	France
11	Centre Suisse de Electronique et de Microtechnique SA	CSEM	Switzerland
12	Sensor Technology & Device Ltd.	STD	UK
13	Steiger	STEIGER	Switzerland
14	Philips Research	PHILIPS	Germany
15	Ciba Specialty Chemicals	CIBA	Switzerland
16	Diadora/Invicta Group	DIADORA	Italy
17	iXscient Ltd.	IXSCIENT	UK
18	Zarlink Semiconductor	ZARLINK	UK
19	Brunet-Lion	BRUNET	France
20	Brigade de Sapeurs-Pompiers Paris	BSPP	France
21	INSA-Lyon-CNRS	INSA	France
22	EUCENTRE Italian Civil Protection	EUCENTRE	Italy
23	Dept. de la Defense et de la Securite Civile	DDSC	France

II. Analysis of the End Users' Needs

ProeTEX addresses different users (Civil Protection rescuers, urban and forest fire-fighters) facing different kinds of emergencies in different scenarios. Each category of users has specific needs in terms of variables to be monitored, operative conditions and compliance to European Standards. For this reason one of the key points since the beginning of the project has been the definition of the sensorized garments specifications, to be set together with the end users involved in the project. Five operative scenarios were hypothesized, in which sensorized garments could be used, [16]: three are representatives of Civil Protection’s major interventions (*violent earthquake and volcano activity in a highly populated area*, *heavy rain or flooding*, *earthquake on a mountain area in winter*), one is representative of the urban fire-fighters activity (*large industrial fire*) and one of the forest fire-fighters activity (*wild-land fire near populated areas*). For each scenario, coordinators of Italian and French Civil Protection agencies, as like as military managers of BSPP were interviewed in order to identify the current intervention practices, environmental difficulties, procedures, information flows, historically most common causes of accidents and injuries to the rescuers.

The requirements raised from Civil Protection authorities, which pointed out the current drawbacks in the interventions management, mainly regarding improvements in remote transmission of information able to identify the actual entity of the emergency, as like as in real-time localization of many (often hundreds) rescuers in large intervention areas where the pre-existing communication networks may be unavailable. The forest fire-fighters’ authorities, whose operators often intervene in large areas where no communication network is available at all, share this request. Detection of possible environmental threats, such as presence of high concentrations of toxic gases, is required to launch immediate alarms to the rescuers. Moreover end users ask for sensors which allow monitoring the operators’ vital signs, in order to prevent possible conditions of physiological distress due to harsh working conditions. In this case alarms should be launched to the intervention managers, coordinating the first-line rescuers from command posts placed

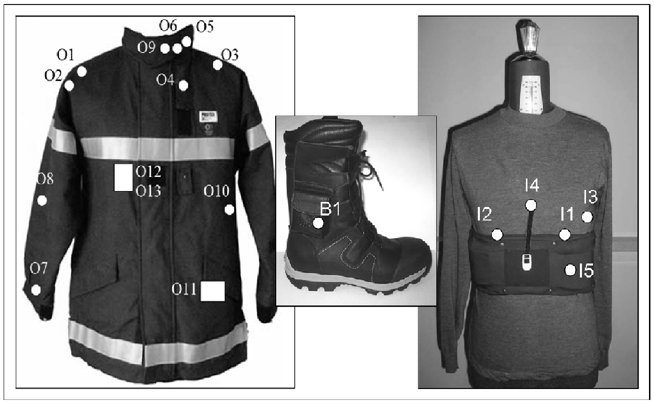

Fig. 1. Overview of the 2nd Prototype. *Left Panel*: OG - external temperature sensor (O1), heat flux sensor (O2), GPS antenna (O3), front visual alarm (O4), acoustic alarm (O5), collar and wrist accelerometers (O6-O7), textile motion sensor (O8), CO sensor (O9), ZigBee module (O10), professional electronic box (O11), Wi-Fi module (O12) and textile antenna (O13). *Central Panel*: boot - CO_2 sensor and ZigBee module housing (B1). *Right Panel*: IG - textile electrodes for HR monitoring (I1), piezoelectric BR sensor (I2); BT sensor (I3), SPO_2 sensor (I4) and vital signs board (I5).

near the disaster area. The most suitable physiological parameters which allow depicting the rescuers' health state were identified by the medical personnel of the First Aid Departments of national importance Italian hospitals (IRCCS Policlinico San Matteo, Pavia and A.O. Ospedali Riuniti, Bergamo) and to BSPP medical representatives.

Urban fire-fighters have different requirements with respect to other users, since they mainly work in small operative areas and their interventions involve few concurrent workers, which usually can be visually monitored. On the other hand working conditions can be really critical, due to presence of fire, possible explosions and toxic gases: these variables should be constantly monitored in order to generate alarms to the rescuers and to the command posts.

In such scenarios fire-fighters already employ commercial toxic gas sensors and activity monitors to detect extended periods of immobility: both the devices are included in the fire-fighters suite designed by ProeTEX. Improvements required by fire-fighters concerning the latter device imply a "smarter" use of the activity monitor in order to reduce as much as possible the number of false alarms which could interfere with the common working activity: for this reason it was required to design an activity monitor allowing not only to detect immobility, but also other potentially dangerous conditions such as falls to the ground, extended periods of immobility of both trunks and arms with the subject lying down, etc., in order to improve the specificity of commercial devices.

III. System Design of Current Release

A. System Overview

Given the aforementioned end-users requirements, the purpose of ProeTEX is the development of a technological infrastructure which allows monitoring first line responders, without interfering with their common working activity and integrating in their interventions' management procedures. In order to reach this goal, the project's consortium is designing both a set of smart garments to be used to acquire physiological, activity and environment related parameters, and the information transmission infrastructure allowing remote data communication, relevant information detection and generation of feedbacks to the users.

ProeTEX prototypes consist of three uniforms addressed to Civil Protection, urban and forest fire-fighters' specific requirements, integrating sensors and electronics. The prototypes are based on a T-Shirt or Inner Garment (IG), a jacket or Outer Garment (OG) and a pair of boots (see Fig. 1). Boots and garments are endowed of wearable multipurpose sensors aimed at real-time monitoring of physiological, activity related and environmental parameters. According to end-user specifications, the monitored parameters are heart rate (HR), breathing rate (BR), body temperature (BT), blood oxygen saturation (SpO_2), environmental temperature, concentration of toxic gases such as carbon monoxide and carbon dioxide, operator's activity and his absolute position and speed. The IG is dedicated to the physiological measurements that need direct contact or proximity with the skin, while the OG and boots measurements deal with activity and environmental parameters. The system core is the Professional Electronic Box (PEB, hosted in the OG), which collects the elaborated information from the sensor nodes.

The sensorized garments represent the main node of the information infrastructure designed by ProeTEX, graphically shown in Fig. 2. Data collected by the PEB are real-time sent to the local coordinator of the operations, by means of a Remote Transmission System working with a Wi-Fi protocol: according to Civil Protection and fire-fighters current emergency management standards, the local coordinator is represented by a mobile command post, usually placed at the margins of the operative area, from which all the activities of the first line responders are overseen. A monitoring software, running on the local coordination workstation, real-time visualizes the information extracted from data and automatically activates alarms when dangerous contexts are detected. Finally, using commercially available technologies for long range communication (i.e. satellite based standards), relevant information can be sent from local coordinators posts to central emergency coordinators (i.e. Civil Protection agencies headquarters): this latter part of the information infrastructure is

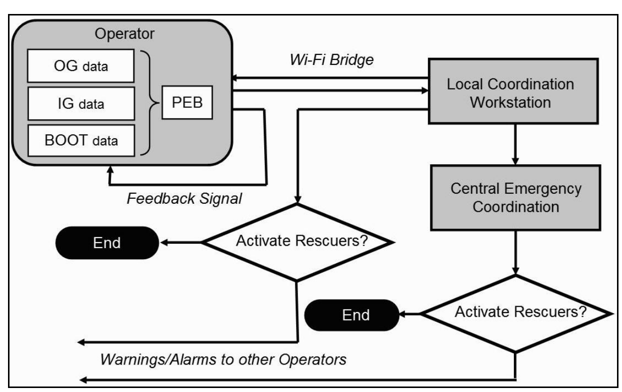

Fig. 2. Information management infrastructure foreseen by ProeTEX

outside the purposes of ProeTEX.

Besides developing technologies for rescuers monitoring, the project's consortium is also developing a Victim Patch (VP) module, which should be used in order to allow health personnel to real-time monitor the vital signs of possible victims of the emergencies.

B. Sensor Modules

Within the ProeTEX concept the processing logic is distributed at the sensor level. Each measurement node is implemented through a dedicated sensor module (Table II) that contains the sensor itself, the analog front-end plus a low power microcontroller which operates the A/D conversion, signal processing and information extraction. The IG and OG modules send the elaborated information to the PEB through a RS485 bus (four wires, two for data and two for power supply, industrial standard for sensors networks). The boot gas sensor is connected to the PEB through a ZigBee wireless link. The sensor modules continuously acquire, convert and elaborate the sensor signals. The PEB sends queries to each module at a predefined time rate. As soon as the module receives a query, it transmits back the requested parameter. This modular architecture allows reducing both the overall hardware complexity and the amount of data to be sent (i.e. minimize transmission power consumption) and allows the system being as versatile as possible (with the possibility of including new sensors without modifying the PEB architecture).

C. Inner Garment

The IG is devoted to assess the health status of the emergency operators through physiological parameters measurements: HR, BR, BT and Oxygen Saturation. The garment is directly in contact with the user skin, thus the operator comfort is the key requirement in order to gain a wide system acceptance. To maximize the user comfort, textile based and/or textile compatible technologies have been employed.

The IG prototype is based on a T-shirt having two main areas devoted to specific tasks: (1) an elastic region including all textile sensors and (2) a region containing a detachable on-board electronics (Vital Signs Board, or VSB). The textile sensors and electrodes are connected to the electronic modules through textile conductive cables integrated in the shirt. Custom designed textile compatible connectors are encapsulated in the fabric and allow the physical connection between the cables and the electronic components. The VSB acquires and processes the IG sensors signals and transmits the elaborated information to the PEB through the RS485 bus. In the third release of the prototype a wireless connection will be realized in order to avoid physical connection between the IG and the OG.

The HR signal is obtained by means of three textile electrodes, realized as described in [17]: a stainless steel based yarn have been knitted together to a ground yarn by using a tubular intarsia technique to get a double face, whereas the external part is not conductive in order to insulate the electrodes from the environment. The raw signal measured by the electrodes is elaborated by means of a proprietary algorithm in order to obtain the HR with a 0.2 Hz throughput. The former ProeTEX prototype employed hydrogel membranes in order to improve the signal quality, the latter uses specific textile solutions that have been adopted to refine the contact between the electrodes and the skin without using the membranes.

The BR sensor is realized by means of two different technologies: both of them use deformation sensors in order to capture local fabric deformations due to respiration chest movements. The resulting signal is a periodic one, which is processed in order to extract its fundamental frequency. The first BR method employs piezo-resistive textiles as described in [18]. The second method exploit the high electromechanical sensititivity of piezoelectric transducers in wire form. This new configuration increased the SNR, making the breathing signal detector more reliable and robust [19].

BT measurement is carried out by using a digital sensor (LM92) sealed in a Polyamide Foil and thermally insulated on one side in order to shield the BT measurement from the effects of the environmental temperature, as described in [20]. The sensor is embedded in the shirt in a proper pocket at the left armpit level. Insulation textile layers have been foreseen.

SpO_2 measurements are exploited through an optical transducer based on CSEM technology, made of several couples of optical emitters and receivers, integrated in a unit at breastbone level. A built-in processor triggers the best located transmitters to dynamically select the highest signal levels; then a processor selects these samples and stores values in a memory.

D. Outer Garment

The OG includes the subsystems for assessing the operator activity state and monitoring the surrounding environment. It is produced in three different configurations, depending on the application: specifically, the prototype for Civil Protection is based on the official uniform of the Italian Civil Protection operators. Urban and forest fire-fighters prototypes use fire-proof jackets adapted from French fire-fighters uniforms.

All the OG configurations include two tri-axial accelerometers, a textile motion sensor, a carbon monoxide sensor and an external temperature sensor. Forest fire-fighters and Civil Protection operators have also an integrated GPS

TABLE II
SENSORS MODULES CONFIGURATION – II PROTOTYPE

Sensor Module	Garment	Function	PEB Interface
Piezoelectric Sensor	IG	Breathing Rate	RS 485
Textile Electrodes, Piezo-Resistive and Body Temp Sensors	IG	Heart Rate, Breathing Rate and Body Temperature	RS 485
SpO2 Sensor	IG	Oxygen Saturation	RS 485
Accelerometer #1	OG	Inactivity Sensor	RS485
Accelerometer #2	OG	Inactivity/Fall	RS485
CO Sensor	OG	CO Concentration	RS485
External Temp. Sensor	OG	Environmental Temperature	RS485
Heat Flux Sensor	OG	Heat Flux across the jacket	RS485
Textile Motion Sensor	OG	Inactivity Sensor	RS485
GPS Module	OG	Absolute Position	Dedicated
CO2 Sensor	Boots	CO2 Concentration	Zigbee

module, whereas urban fire-fighters do not, since they operate inside buildings where reliable GPS signals are rarely available. Moreover a Heat Flux sensor has been included both in the urban and forest fire-fighters OGs, in order to prevent operators sudden uniform burning (due to high thermal insulation of the fire-proof jacket, the operator has a low feeling of the actual outside temperature). Regarding the data transmission, all the OGs incorporate a long range transmission module (see *Section III.F*). The garments include also an Alarm Module, that is a subsystem launching visual and acoustic warnings when one or more sensors detect operator dangers beforehand.

A commercial Lithium Ion-Polymer battery, allowing an autonomy of up to seven hours of functioning, gives the power supply to the garment electronics. Moreover a prototype flexible battery, specifically designed for the project, allows to increase the system autonomy of up to two hours [21].

The External Temperature (ET) module is placed under the OG external coating (waterproof, not thermally insulating) at shoulder level; this set-up avoids environmental disturbances and optimizes higher temperature detection [20]. The Heat Flux sensor is placed in the proximity of the ET module, under the thermal insulating layer of the OG, at shoulder level as well.

The GPS Module is based on the ANN-MS-0-005-0 active GPS antenna from U-Blox. It provides an accurate measure of the absolute position of the user, when in open space (outdoor and far from buildings or high obstacles). Unfortunately the sensor's performance drastically decreases when approaching or entering into buildings. In any case this information is considered as really important by rescuers working in large operative areas, where they can't be visually monitored.

The Alarm Module was designed by CSEM and it is made of a power red LED driven by a microcontroller which makes it flashing at different frequencies depending on the type of alarm. It includes also an audio alarm board with a buzzer control.

The ProeTEX motion sensor is used to detect long periods of user immobility and user falls to the ground and it is realized by means of two tri-axial accelerometer modules. One accelerometer is placed in the higher part of the trunk in order to detect inactivity and falls to the ground. The second sensor is located in the wrist region and its aim is to achieve more accuracy in inactivity detection, since an operator can move his arms while the trunk is not moving. The core of the motion sensor is the processing algorithm detailed in [22], which allows to perform a reliable estimation of the body inclination even in the case of an intense physical activity.

In order to gain more redundancy in monitoring the operator movements, a Textile Motion Sensor is applied to the external part of the OG insulation layer, and used to detect operator arm motion: the technology of the textile deformation sensor is described in [23] and integrated in the sleeve's elbow region.

Carbon monoxide is an extremely toxic gas with density comparable to air; therefore a CO sensor module is placed in the OG lapel near the user's mouth and nose. The sensor is integrated in the outer shell layer of the OG, while electronics is protected from the heat by fixing it under the thermal insulating layer. A waterproof gas permeable coating protects the sensor. The on-board firmware implements a calibration curve and sends the gas concentration in percentage with respect to a dangerous threshold.

E. Boots

Boots prototypes were developed and tested both for Civil Protection and fire-fighter brigades. From the structural point of view, the prototypes satisfy EU standards and are arranged for integrating sensors and energy harvesting elements.

Following the end-users requests, a Carbon Dioxide (CO_2) sensor is integrated in the boot upper part in a specific housing, capable of maintaining the sensor in contact with the air. The CO_2 detector has been placed in the shoe since the target gas is heavier than air and starts to accumulate at ground level. The module is based on the CO_2-D1 Alphasense sensor, a processor for the data acquisition and processing plus a ZigBee module for the communication with the PEB. The on board firmware implements a calibration curve and sends the gas concentration in percentage with respect to a dangerous threshold.

F. Remote Transmission and Monitoring

Besides wearable technologies for sensing and data processing, a remote communication network was developed, allowing to transmit recorded data to the command post overseeing the operator's work. It is based on a *long range communication system* and a *monitoring software* [24], and was designed to complete the users – local coordination workstation part of the information flow infrastructure in Fig. 2.

The *long range communication system* manages the bidirectional data transmission between the PEB of each

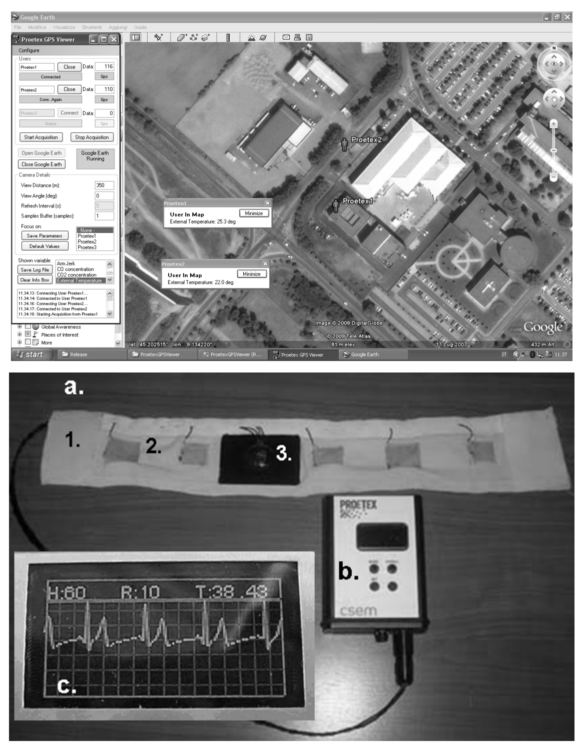

Fig. 3. *Upper panel*: the main interface of the monitoring software. *Lower panel*: *a.* Victim Patch: 1. adhesive strips for fastening to the subject's chest; 2. electrodes; 3. BT sensor. *b.* Victim Electronic Box. *c.* detail of the display.

operator and the PC of the local coordinator through a potentiated Wi-Fi system; this solution was chosen as a good compromise between the portability, lightness and performance. A modular network was developed: the operators working in the emergency area are provided with a transmission system located in the breast pocket of the OG (an embedded PC board running Linux operative system, provided with a Wi-Fi board) which acquires the data from PEB and wireless transmits them through two textile antennas within the jacket [25]. Data coming from the operators are real-time received and remotely re-broadcasted by a self powered bridge module, placed on a tripod at the edge of the operative area and provided with directional antennas for long range communication (a maximum distance of 1.3 km in open space is allowed). Data are received by a node identical to the former one, which is connected to the emergency coordination workstation.

The *monitoring software* allows to visualize the position of each operator on a map as well as all his/her data measured by the PEB. The graphic interface is based on Google Earth® software, and associates an icon representing each operator on the Google Earth map to the alarms and warning flags automatically generated by processing the relevant data (Fig. 3, upper panel). The “intelligence” required to automatically process and fuse data coming from the different sources (with particular attention to tasks such as activity recognition [22] and physiological monitoring) is currently matter of investigation.

G. *Victim Patch*

The Victim Patch is a textile device with the same features of the IG, devoted to monitor the vital signs of potential victims: it is made of a textile patch containing the HR, BR and BT sensors to be placed on lying subjects’ chest or abdomen; fastening of the textile patch is done by means of adhesive strips fixed at the border of the device. A Victim Electronic Box (VEB) captures the raw signals, processes them and shows the extracted features directly on a display; moreover the VEB real-time transmits the data to the monitoring software through a Bluetooth integrated module (Fig. 3, lower panel).

IV. System Validation

Great attention was paid to the prototypes’ tests, in order to assess each feature of the sensorized garments both from a technical point of view and from a usability point of view, given the expectations and needs of the end-users. For this reason a whole work-package of the project, involving industrial partners and end-users, is dedicated to the systems validation. Tests on the single sensors and devices, as well as on the whole equipments, were carried out in specialized laboratories.

As already mentioned, three categories of devices are included in the sensorized garments: commercial devices suitable for direct integration into clothing (i.e. the GPS module, environmental temperature and toxic gases detectors); commercial devices customized for application to ProeTEX prototypes (i.e. the accelerometers with custom developed firmware, remote transmission system based on commercial embedded computers, the thermocouple for BT measurement with custom designed insulation); custom developed prototypes (i.e. the heart and respiratory rate sensors).

Assessment of the former category of devices was done to detect possible malfunctioning of the commercial systems once integrated into garments and to evaluate whether accuracy and reliability of the measures reflected real users’ needs. All devices demonstrated to be compliant with the end-users requirements and specifications.

A special attention was paid to the assessment of the remaining devices; since the sensors for physiological parameters monitoring represent the most challenging aspect of ProeTEX, this section is mainly focused on the tests carried out on them. Furthermore, results of the validation procedures on accelerometers modules and remote transmission system have been already reported in published works [22], [24].

The main purpose of testing physiological variables sensors concerned the evaluation of their reliability in presence of factors potentially affecting the electronic performance, due to the environment (e.g. high temperature) or to human related variables (intense physical activity and perspiration).

A. *Materials and Methods*

HR, BR and BT sensors were tested at the Thermo -Physiology Laboratory of the Centre de Recherches du Service de Santé des Armées (CRSSA) in Grenoble, France: this laboratory is equipped with a climatic chamber in which arbitrary conditions of temperature and humidity can be set. Inside the climatic chamber a treadmill allows to simulate activities such as walking and running, on a flat or sloping surface. Gold standard instrumentation was used as a reference for measuring the three variables: namely, a SuperMon 7210 monitor (by Kontron Instruments, Watford, UK) for the HR, a commercial spirometer (model HS 255N by CB Sciences, Inc, Dover, USA) for the BR and a rectal probe for BT measurements. Concerning the first device, it was set in order to record one ECG lead (by means of commercial patch electrodes), with a sampling frequency of 1 kHz, to detect QRS waves on the signal and to extract the HR value: this variable was updated at 0.1 Hz (each output representing the average HR in a 10 s wide time window). According to medical specialists, such an update rate is enough accurate in order to monitor health state of subjects performing intense physical activity. On the other hand, BR was extracted from raw respiratory signal by real-time computing the frequency corresponding to peak of the signal’s power spectrum in 20 s wide time windows.

Six adult male subjects participated to the experiments: twelve acquisitions were executed in the climatic chamber, with a relative humidity set at 20 % and environmental temperatures set at 20 °C (three trials), 35 °C (five trials) and 45 °C (four trials) respectively. Each session consisted of the following sequence of activities: resting for five minutes outside the climatic chamber (defined as activity *R1*), walking on the treadmill at 4.0 Km/h inside the climatic chamber (with initial slope set at 4 % and increased of 2 % every fifteen minutes, up to 10 % – activities *A1*, *A2*, *A3* and *A4* respectively) and resting outside the chamber for five minutes (*R2*). During each session the subject worn both ProeTEX and reference instrumentation, and was monitored by medical personnel, in order to stop the experiment whenever dangerous health state conditions were detected (stop conditions were decided by establishing thresholds of maximum BT and HR): three (of four) trials carried out at 45 °C were stopped few minutes before the expected end, due to overcoming of these thresholds.

Finally a comparison between the performance of the ProeTEX sensors vs. the reference ones was done by measuring the average error of each monitored variable in every environmental set-up and by analyzing the performance degradation vs. time (due to the increasing subject's perspiration and activity intensity).

B. Results

The results concerning the three sensors under examination, in terms of average error (± standard deviation) as a function of the different environmental temperatures, are shown in the Table III: values of each column are the average and standard deviation extracted from data of all the trials carried out by different subjects at the same environmental conditions. Average errors of the three sensors, as a function of the activity carried out by the subjects (R1, A1, A2, A3, A4 and R2) are graphically shown in Fig. 4: each subplot reports the average error calculated over all the data of the different subjects at specified environmental temperature and activity.

C. Discussion

The results of Table III and Fig. 4, obtained by analyzing more than 13 hours of recordings, demonstrate the potential of wearable instrumentation developed by the ProeTEX consortium in order to monitor the rescuers vital signs, also in harsh environmental conditions.

Concerning the HR, a measurement error lower than 10 beats per minute can be considered as acceptable in order to identify dangerous health state conditions. Such a result was reached during almost all the trials carried out at 20 °C and 35 °C: malfunctioning were detected only during high intensity activities at 45 °C, and were probably due to the high perspiration of the subject (according to the established protocol, walking at 4.0 Km/h on a 10 % slope was carried out after 45 minutes of walking in harsh environment). The effect of sweat in terms of performance worsening was proved by high average error also during the final resting at the end of the exercise: this fact allows excluding motion artifacts as the main cause of this worsening.

Similar conclusions can be drawn about the BR sensor. The sensor's average error increases when the environmental temperature increases too; nevertheless, results at 20 °C and 35 °C are widely acceptable. Only after extended exposition to harsh environmental conditions, the system starts producing unacceptable outputs (the error is about 10 cycles per minute during *A3* and more than 20 cycles per minute during *A4* at 45 °C). Moreover, as regards the HR and BR sensors, it should be remarked that in the current version of the prototypes the environmental conditions, causing malfunctioning in the systems, are the same which caused the early interruptions of the experiments due to possible physiological dangers for the physically trained subjects. Further improvements both to the textile part (aimed at improving insulation of the textile wires and connectors within the IG and stabilizing the electrodes impedance) and to the electronics are expected to improve the next prototypes and extend usability in harsher conditions.

Finally, concerning the BT sensor, widely acceptable results were obtained during the tests, especially considering that the ProeTEX device measures the skin temperature, and it was compared to "gold standard" sensor measuring the internal BT. Indeed, even if the sensor output was still partially influenced by the environmental temperature (an overestimation of the actual value was obtained during trials at 45 °C, whereas an underestimation was found during those at 20 °C, see the Fig. 4, bottom panel), it allows to estimate the actual BT with an average error lower than 1 °C during almost all the acquisitions.

TABLE III
PHYSIOLOGICAL SENSORS PERFORMANCE: AVERAGE ERRORS VS GOLD STANDARD INSTRUMENTATION (± STANDARD DEVIATION)

Ext. Temp.	Heart Rate (bpm)	Breath. Rate (cpm)	Body Temp. (°C)
20°C	-4.00 ± 10.55	0.63 ± 3.17	-0.36 ± 0.60
35°C	0.71 ± 2.47	-2.85 ± 5.43	-0.04 ± 0.52
45°C	-2.66 ± 19.50	4.49 ± 15.99	0.36 ± 0.93

V. FUTURE DEVELOPMENTS

The wearable system described in this paper represents a partial result of the project, since a third set of sensorized garments will be delivered in January 2010. The new version will contain two novel sensors, namely a dehydration detector based on biochemical sensing technology, to be placed in the IG, plus a novel activity sensor, made of organic electronics

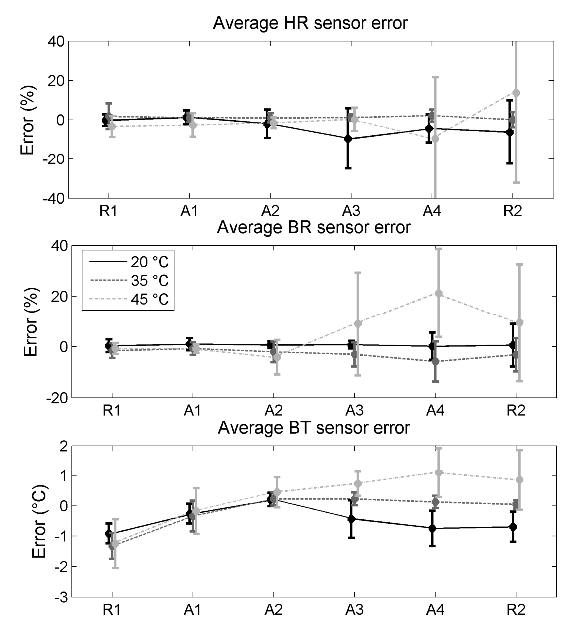

Fig. 4. Performance of the ProeTEX system in measuring heart rate, breathing rate and body temperature in the subsequent activities of carried out protocol. Different lines refer to the average results obtained with different environmental temperatures; for each activity the average error (among all the trials carried out at the specified temperature) ± standard deviation is reported.

[26] and located within the boot. A part from updating the sensors network with these devices, the partners of ProeTEX consortium are studying and developing new optical bio-sensors for the stress detection, non contact radio frequency sensors for physiological and thermal parameters monitoring [27], [28] and energy scavenging systems.

Besides technological novelties, a specific task of the project is dedicated to the development of "smart" algorithms for the data interpretation and fusion, in order to extract useful information about the subject physical and physiological state and to point out possible dangerous health state conditions. Current studies are focused on the data fusion of accelerometric derived indexes (detection of posture, activity level, and deambulation) with physiological parameters (HR, BR). Successful results of this ongoing task will be considered for implementations in the final version of the monitoring software, with the purpose of simplifying the remote surveillance of an arbitrarily high number of rescuers through a single and user-friendly interface.

Once the final system is realized, the last months of the project will be dedicated to an intense "in field" validation, consisting of simulated interventions of urban and forest fire-fighters in training centres of the Italian and French Civil Protection and of BSPP. As mentioned in the previous section, harsh environmental conditions can be also simulated during laboratory trials, whereas during field trials it is not possible to use reference instrumentation which can be available in laboratory. Nevertheless, this latter validation activity was foreseen in ProeTEX because it allows to assess the "global performance" of the sensorized garments and data management infrastructure in real scenarios, with several rescuers wearing the smart garments and working together, according to their practices and carrying all the tools and materials they already use during daily activities (i.e. oxygen bottles and tools belt). Sensorized garments will be assessed during field trials in terms of reliability of the system (detection of losses of connections between users and monitoring post, partial or definitive unavailability of any of the detected signals, false alarms generated by the instrumentation). Furthermore, final field trials represent an important opportunity for the project exploitation plan, in order to select, among all the developed technologies, the most useful and suitable for inclusion in the possible future market products rising from this research.

VI. References

[1] P. Lukowicz, "Human Computer Interaction in Context Aware Wearable Systems," *Artificial Intelligence in Medicine,* Springer ed 2005, pp. 7-10.

[2] A. Lymberis, "Research and development of smart wearable health applications: the challenge ahead," in *Wearable eHealth Systems for Personalised Health Management: State of the Art and Future Challenges* IOS Press, 2004, pp. 155-161.

[3] D. Marculescu, R. Marculescu, N. H. Zamora, P. Stanley-Marbell, P. K. Khosla, S. Park, S. Jayaraman, S. Jung, C. Lauterbach, W. Weber, T. Kirstein, D. Cottet, J. Grzyb, G. Tröster, M. Jones, T. Martin, and Z. Nakad, "Electronic textiles: A platform for pervasive computing," *Proc. IEEE*, vol. 91, no. 12, pp. 1995-2018, 2003.

[4] E. Jovanov, "A Survey of Power Efficient Technologies for Wireless Body Area Networks" *Conf Proc IEEE Eng Med Biol Soc*, p. 3628, 2008.

[5] P. F. Binkley, "Predicting the potential of wearable technology," *IEEE Eng. Med. Biol. Mag.*, vol. 22, no. 3, pp. 23-27, 2003.

[6] S. Park and S. Jayaraman, "Enhancing the quality of life through wearable technology," *IEEE Eng. Med. Biol. Mag.*, vol. 22, no. 3, pp. 41-48, 2003.

[7] J. Lauter, "MyHeart: Fighting cardiovascular disease by preventive and early diagnosis," in *Wearable eHealth Systems for Personalised Health Management, Studies in Health Technology and Informatics*. A. Lymberis and D. De Rossi, Eds. 2004, pp. 34-42.

[8] C. Gopalsamy, S. Park, R. Rajamanickam, and S. Jayaraman, "The wearable motherboard: the first generation of adaptive and responsive textile structures (ARTS) for medical applications," *Journal of Virtual Reality*, vol. 4, pp. 152-168, 1999.

[9] http://nsrdec.natick.army.mil/about/techprog/index.htm

[10] http://www.viking-life.com/

[11] www.systematic.dk/

[12] A. Lymberis and A. Dittmar, "Advanced Wearable Health Systems and Applications Research and Development Efforts in the European Union," *IEEE Eng. Med. Biol. Mag.*, vol. 26, no. 3, pp. 29-33, 2007.

[13] P. Lukowicz, A. Timm-Giel, M. Lawo, and O. Herzog, "WearIT@work: Toward Real-World Industrial Wearable Computing," *IEEE Pervasive Computing*, vol. 6, no. 4, pp. 8-13, 2007.

[14] M. Klann, "Playing with Fire: User-Centered Design of Wearable Computing for Emergency Response," *Mobile Response: Mobile Information Technology for Emergency Response*, pp. 116-125, 2007.

[15] www.proetex.org

[16] A. Bonfiglio, N. Carbonaro, C. Chuzel, D. Curone, G. Dudnik, F. Germagnoli, D. Hatherall, J. M. Koller, T. Lanier, G. Loriga, J. Luprano, G. Magenes, R. Paradiso, A. Tognetti, G. Voirin, and R. Waite, "Managing Catastrophic Events by Wearable Mobile Systems," *Conf. Proc. Mobile Response*, pp. 95-105, 2007.

[17] Knitted textile for the monitoring of vital signals, WO2005053532, 2005.

[18] G. Loriga, N. Taccini, D. De Rossi, and R. Paradiso, "Textile sensing interfaces for cardiopulmonary signs monitoring," *Conf. Proc. IEEE Eng. Med. Biol.*, pp. 7349-7352, 2005.

[19] T. Faetti, A. Lanatà, E. Nardini, E. P. Scilingo, and D. De Rossi, "A comparative evaluation of different techniques for ambulatory monitoring of respiratory rate," *International Workshop on Wearable Micro and Nanosystems for Personalised Health (pHealth2008)*, 2008.

[20] A. Oliveira, C. Gehin, G. Delhomme, A. Dittmar, and E. McAdams, "Thermal Parameters Measurement on Fire Fighter During Intense Fire Exposition," *Conf. Proc. IEEE Eng. Med. Biol. Soc.*, pp. 4128-31, 2009.

[21] S. Bacquet, H. Rouault, H. Lhermet, E. Crochon, H. Lignier, S. Martinet, M. Martin, and L. Sourgen, "PeacPocket : a technological demonstrator for future multimedia smart card," *Smart Object and Ambient Intelligence Conference (SOC 2005)*, pp. 297-302, 2005.

[22] G. Anania, A. Tognetti, N. Carbonaro, M. Tesconi, F. Cutolo, G. Zupone, and D. De Rossi, "Development of a novel algorithm for human fall detection using wearable sensors," *IEEE Sensors*, pp. 1336-1339, 2008.

[23] A. Tognetti, R. Bartelesi, F. Lorussi, and D. De Rossi, "Body segment position reconstruction and posture classification by smart textiles," *Trans. of the Institute of Measurement and Control*, vol. 29, no. 3-4, pp. 215-253, 2007.

[24] G. Magenes, D. Curone, M. Lanati, and E. L. Secco, "Long distance monitoring of physiological and environmental parameters for emergency operators," *Conf. Proc. IEEE Eng. Med. Biol. Soc.*, pp. 5159-5162, 2009.

[25] C. Hertleer, H. Rogier, L. Vallozzi, and L. Van Langenhove, "A Textile Antenna for Off-Body Communication Integrated into Protective Clothing for Firefighters," *IEEE Trans. Antennas Propag.*, vol. 57, no. 4, pp. 919-925, 2009.

[26] I. Manunza, A. Sulis, and A. Bonfiglio, "Pressure and strain sensing using a completely flexible organic transistor," *Biosensors & Bioelectronics*, vol. 22, pp. 2775-2779, 2007.

[27] A. Fonte, F. Alimenti, D. Zito, B. Neri, D. De Rossi, A. Lanatà, and A. Tognetti, "Wearable system-on-a-chip radiometer for remote temperature sensing and its application to the safeguard of emergency operators," *Conf. Proc. IEEE Eng. Med. Biol. Soc.*, pp. 5715-5718, 2007.

[28] D. Zito, D. Pepe, B. Neri, D. De Rossi, A. Lanatà, A. Tognetti, and E. P. Scilingo, "Wearable system-on-a-chip UWB radar for health care and its application to the safety improvement of emergency operators," *Conf. Proc. IEEE Eng. Med. Biol. Soc.*, pp. 2651-2654, 2007.