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Smart Sensing Uniforms for Emergency Operators

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Abstract. Textile integration of smart sensor systems is the key technology for the success of future e-garments oriented to emergency operators. Ubiquitous recording and transmission of human and environmental data will allow combining comfort and protection leveraging with the existing smart textile, microelectronics and telecommunication technologies. The challenge offered by emergency situation is mainly in the difficulty to acquire data in a very aggressive environment, during hard physical activity; conditions that will increase the risks of signals artefacts, as well as the presence of positive and negative false events.
Security is addressed through the implementation of systems combining body sensing platform, for health alertness and environment sensing platform for context awareness; the full system has also to guarantee protective functionality. State of art textile technology allows the monitoring of heart and respiratory rate, humidity rate, activity rate, GSR and EMG, while core and external temperature, posture via accelerometers, absolute position via GPS are easily monitored through standard sensors. The body sensing platform requires a direct contact with the operator skin leading to the implementation of a sensing inner garment, at the same time environment platform are integrated in a protective jacket that is also hosting the alarm systems and the electronic unit for signal processing and transmission hardware.
This paper is reporting about a study done with a pioneer e-textile system named Wealthy on healthy subjects during extreme conditions.
Wealthy platform is currently evolving in a new one, specially designed for emergency scenarios, developed in the frame of the project Proetex, a preliminary description of the new system is presented; the new system that is under first testing phase, has been designed to be used without interfering with operator activities.

Introduction

Research and development in smart wearable systems and applications for personalized services, especially for monitoring purposes, has significantly increased worldwide over the last few years [1]. The motivation in the health areas is guided by the need to guarantee an high level of security and safety during emergency scenarios for the operator, providing easy access to all the environmental information from anywhere, anytime, to as many people as possible.
Smart, wearable monitoring systems [2] have the capability of supporting the extension/expansion of health monitoring services outside the domain of classical establishments, and monitoring users over extended periods of time. New promising research recently emerged from the miniaturization

of electronics and informatics (computers, microsensors, signal processing, transmissions, etc.), making possible the integration of multiple, smart functions into textiles, free from any impediment. Smart fabrics leading to e-textiles substrates are considered relevant promoters of a higher quality of life and progress for biomonitoring, rehabilitation, telemedicine, teleassistance, ergonomics and sport medicine. Biomonitoring, meaning both cardiopulmonary function body and kinematics monitoring, would considerably benefit from the implementation of wearable sensorized systems. In particular, the integration into clothes of several kinds of biosensors for health monitoring would provide daily physiological parameters through a continuous, personalized, and self-made detection of vital signs, while garments with strain- and stress-sensing capabilities [3] would enable the tracking of posture and gestures of a subject, and would permit the precise analyses of kinematic variables of interest.

Continuous monitoring ensures the capture of relevant events and the associated physiology during routinely working activities, systems can be personalised according the risks rising from the specific emergency scenarios like fire, earthquake, flood, as well as for ordinary activity, explosions, gas leaks, or more simply any situation at risk. Data will have a double use; an immediate alert to optimise the emergency operations, a secondary statistical use for learning purposes. Long term monitoring has the potential to help create new models of behaviour at risk for the operator and the team over time at resolutions currently unobtainable.

These systems comprise innovative fabric sensors for ECG, breathing rate, temperature, trans-thoracic impedance, SpO2 measure and sweet analysis. The systems have to be used un-obtrusively into the routinely working activity of the user. Additional sensors are integrated in the on-body electronics for the detection of movement and the detection of context information (e.g. GPS location). The core of the electronic system is usually based on a scalable low-power processing unit that can be designed according to different applications needs. The system not only allows the acquisition and storage of data, but also the online analysis of the data and has to provide the needed processing power for diagnosing the health status. Ad hoc signal and data processing procedures have to be developed for each scenario, in order to provide personalized and synthetic parameters related to emergency status and its variations in respect to a “reference” situation.

On top of that, wireless technology is used to seamlessly connect the system to wired and wireless communication infrastructure and to acquire data from external sensors and from a centralised control unit. As it is designed as an open, modular system, additional (future) sensors or processing modules or specific user needs can be implemented later on.

Feedback to users: The intelligent biomedical clothes can provide detailed and precise information on user’s health and environmental conditions. This information have to be translated into direct recommendations: according to the experts’ indications, instruction and information could be directly transmitted to the operator. The end user terminals are designed to visualize the recommendations on the mobile setting, anytime and anywhere. Health status as well as instructions for preventive actions can be displayed automatically on mobile terminals as well as on the connected central unit. Special emphasis has to be devoted on the ease-of-use aspects in the context of use.

Remote Access and Professional Interaction: Innovative interactive communication systems will connect the user to the professional assistance services and to the other operators in the mobile setting. There is need for specific application modules that enable the data managing and the operator’s interactions as well as the coordination of the intervention at all the levels: civil and professional.

At risk events detection: Solutions need to be developed to continuously analyse the vital signs of the operator and the environment in order to determine and prevent at risk events.

During emergency, the operator may behave dangerously or may over estimate physical conditions: often during emergency scenarios the workers are over fatigued, nervous and tired; sometime the decisional capability is compromised.

Continuous monitoring may be able to detect signs of changes in respect to the usual acting style and to prevent risky behaviours. Challenge in these applications is the extrapolation of measurable indexes correlated with risky behaviour, considering that signals are recorded through non obtrusive sensors in a very aggressive and noisy environment.

WEALTHY, the pioneer system

WEALTHY system has been developed in the frame of a European funded project (IST-2001-37778) as the integration of several function modules, as it has been presented in previous works [4]. The main functions of the modules are namely sensing, conditioning, pre-processing, data transmission and remote monitoring.

Sensing module consists of the garment connected with the Portable Patient Unit (PPU), where local processing as well as communication with the network is performed.

The PPU is small and lightweight, only 145g., it is easy to use, with two LEDs and a buzzer for user-warning purpose and a button to let a manual trigger of alarm, data transmission is done over GPRS link. The device is powered by a Li-Ion battery autonomy up to 4 hours with real time streaming of all signals over GPRS

ECG signals are sampled on the PPU at 250Hz where a local processing is applied in order to extract parameters with the highest sampling rate, in a way to compute ECG parameters, such as heart rate (HR) value and QRS duration.

The complete list of the signals interfaced by the PPU is given below:

- Six ECG electrodes configurable in Einthoven configuration (lead I, II and III) and Wilson configuration (V2 andV5). Only one lead is transmitted at a time (for GPRS bandwidth limitation reasons). The ECG lead to be transmitted can be selected remotely by the monitoring center.
- Respiration by impedance measurement
- Up to four I2C skin temperature sensors (monolithic circuits)
- One 3D accelerometers (integrated in the unit)
- Four piezo-resistive strain sensors
- SpO_2 (oximetry) from a commercial device (NONIN) (serial interface and power supply provided)

In order to offer full mobility to the patient or the user, acquired signals are wirelessly transmitted from the PPU to the remote Monitoring System. The communication is based on TCP/IP that is the standard protocol for GPRS communication. All signals are sent in quasi real-time to the Remote Monitoring Centre.

A different version uses Bluetooth connection for short range transmission.

Evaluation of the WEALTHY shirt for healthy subjects

To assess the effect of sweating and movement on sensors performance, the reliability of the Wealthy System (WS) has been evaluated with healthy subjects at rest, during exercise and in hot and humid conditions. These particular experimental conditions, which are devised to mimic, for example the environmental situation during a fire, are reproduced in suitable chambers in which both temperature and degree of humidity can be modified in a controlled and reproducible manner.

These paradigms allow verifying the effect of wearing full professional equipment on WS performance. The main objective of this work was to assess feasibility of the use of WS system in extreme conditions and to verify that the physiological signals monitored by WEALTHY device are reliable and satisfactory for a physician. It is not that usual for a physician to monitor vital signs from healthy working subjects; for this reason, it was difficult to select a non obtrusive “gold standard” portable recording device. The study was done by comparing the performances of WEALTHY system with respect to Vitaport III, in the recording of ECG and respiration signals on healthy subjects. As none of the recording available systems was optimised for this purpose and usable in a real working environment, recordings were made either during simulated working activity in the lab or during nights.

Materials and methods

Subjects

Seven (7) male subjects volunteered to participate in the study. Their average body characteristics are presented below.

Main characteristics	Mean ± SD
Age (yrs)	31 ± 5.6
Weight (kg)	68 ± 6.6
Height (cm)	175.7 ± 5.4
Chest perimeter (cm)	95.4 ± 5.3

Fig. 1 : Wealthy shirt and Vitaport ready to be used. Wires from the skin electrodes used by the Vitaport are visible.

All acquisitions were carried out with the Wealthy System and the Vitaport III® (Temec Instrument bv, the Netherland) as reference polygraphic recorder (Fig. 1). Vitaport III® is a portable versatile system which can be set for any kind of electrophysiological or respiratory data acquisition. It is commonly used for ambulatory polygraphic recordings in hospital "sleep unit" in Europe and can be considered as a "gold standard". For this study, a setting was choose to be as closed as possible to the WEALTHY system one, i.e. ECG on five leads (DI, DII, DIII, V2, V5) at 128 Hz and respiration movements by standard resistive plethysmography at 16 Hz.
Clock of both systems were synchronized just before the recordings to allow the comparison of the signals. Every measurement were made according to the same general procedure: simultaneous acquisition with both reference system ("R", Vitaport III device) and WEALTHY system ("W"), both systems being set in order to obtain the best on-line signal during the preparation phase, thereafter no attempt to ameliorate the signal was done whatever it was along the "recording period". The recording period is therefore the period during which comparison between signals was performed.
Three different experimental protocols were set:

1. Short acquisition (45 to 90 min) in a controlled normal conditions (CN): experiments were carried out in the laboratory during resting conditions (fig. 4.2) or during light exercise (walking or light movements, Fig. 2)
2. Short acquisition (45 to 90 min) in a controlled harsh conditions (CH): experiments were carried out into a climatic chamber set at 45 °C Tdb / 60 % at rest or during light exercise (ergocycle, Fig. 2). In these conditions, the tympanic temperature was measured as a core

temperature, for safety reason the subject was not let to reach core temperature greater then 38.5 °C.

3. Long acquisition (5 to 7 hours) in a "natural" setting (NS): full night experiments were carried out at "home" during the sleeping period.

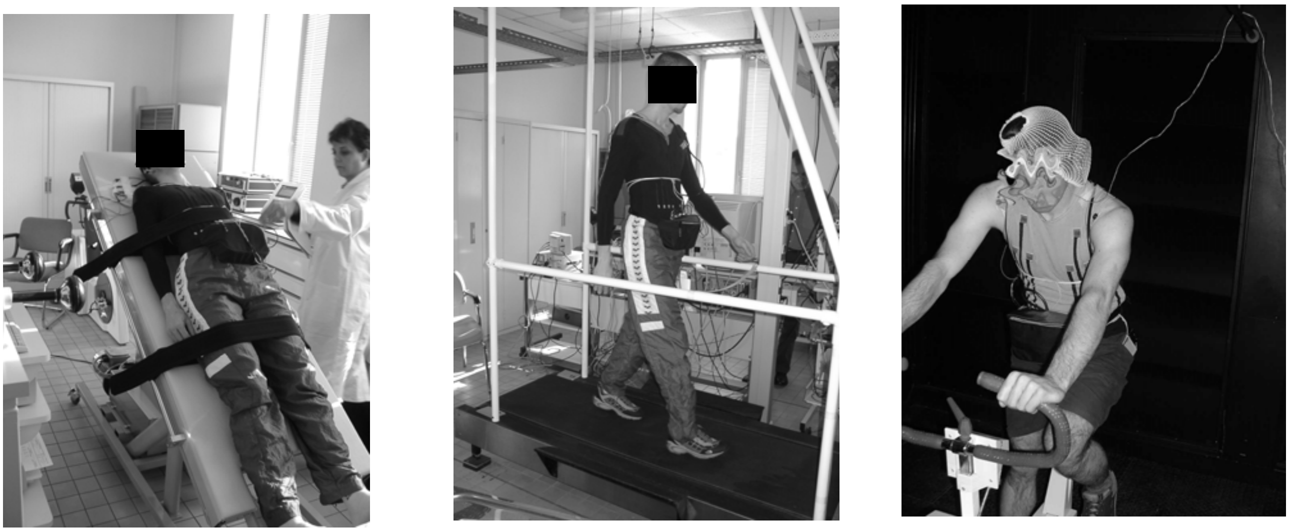

Fig. 2 On the left tilt test during a short experiment, the subject is resting on a table which is quickly raised up at a certain moment. On the center: a walking period during a short experiment. On the right, subject wearing the second version of the WEALTHY jacket exercising on an ergocycle into a climatic chamber set at 45°C Tdb, 60% relative humidity.

During CN condition, the subjects first performed a "tilt-test" then a mix of resting and walking periods on a treadmill. During the tilt test, the subjects are first resting in supine position on a table, after 15 min the table is quickly raised in vertical position; this test challenges the cardiovascular system because there is no muscular work which contributes to the normal adaptation of standing up. During CH condition, the subjects performed a mix of resting and cycling periods on a cyclo-ergometer placed into the climatic chamber. The test ended when core temperature of the subject reached 38.5 °C or after 60 min of exposure. During NS condition, the subjects started the recording just before going to bed, with the instruction to do nothing about the recording till the normal wake-up. Clock of both systems were synchronized everyday to allow the comparison of the R and W signals.

Signal analysis

1) Data visualization

For each experiment, two sets of data were acquired: "R" with the Vitaport III reference system and "W" with the WEALTHY system. All signals were acquired, digitalized and stored in binary files in real time. Each R data file was converted in one EDF (the standard "European Data Format") file prior to analysis, and each W data file was converted in 3 separate text files: one for the ECG, one for the respiratory movement (RESP) and one for the accelerometer signals (ACL).

A converting software was developed to merge the three text files in one after RESP and ACL signals were over-sampled to synchronize them on ECG sampling rate since WEALTHY system sampling rate was 128 Hz for ECG, 16 Hz for ACL and RESP.

Data sets were then visualized with the Prana Viewer ® (Phitools sarl, France) software able to read both EDF and Text files (Fig. 3).

2) Data qualitative analysis

There is up to now no universal standard criteria based on ECG and respiratory trace used to assess whether a healthy subject is still healthy or is going wrong; however, most of the devices used for that purpose are using index based on either the heart rate or the respiratory rate. Indeed, a healthy subject should have a normal ECG and an accident would unlikely change the shape of the trace; it is therefore supposed that the regulation of the cardiac function (cardiac blood flow adaptation through mainly a heart rate change) is the index one have to look at when surveying healthy worker.

Visual analysis was therefore performed aiming at determining whether the signal allowed the determination of the heart/respiratory rate or better. Actually, ECG signal was considered as not interpretable (quoted 1), poorly interpretable (only for the determination of RR intervals allowing the heart variability analysis; quoted 2), difficult to analyse (quoted 3) and good (quoted 4). RESP signal was considered as not interpretable (quoted 1), poorly interpretable (allowing just the calculation of the respiratory frequency, quoted 2), difficult to analyse quoted 3) and good (quoted 4) when it would have allowed an estimation of the respiratory volume. Each recording was divided in epochs of 15 sec long displayed separately on which the quotation was made (Fig. 3). When quality of the signal changes during an epoch, it was quoted the worst which lasts at least about one third of the epoch (5 sec). This procedure leads to a vector of entire values comprised between 0 and 4 for every experiment. R and W vectors from same experiment were then synchronized and data statistically analysed using Excel® (Microsoft Corporation). As most of the experiments started and finished with periods of very noisy signal, mainly due to important movements, the quotation was done only on large samples randomly choose during the experiment. Part of the recordings not visually quoted was assigned to zero.

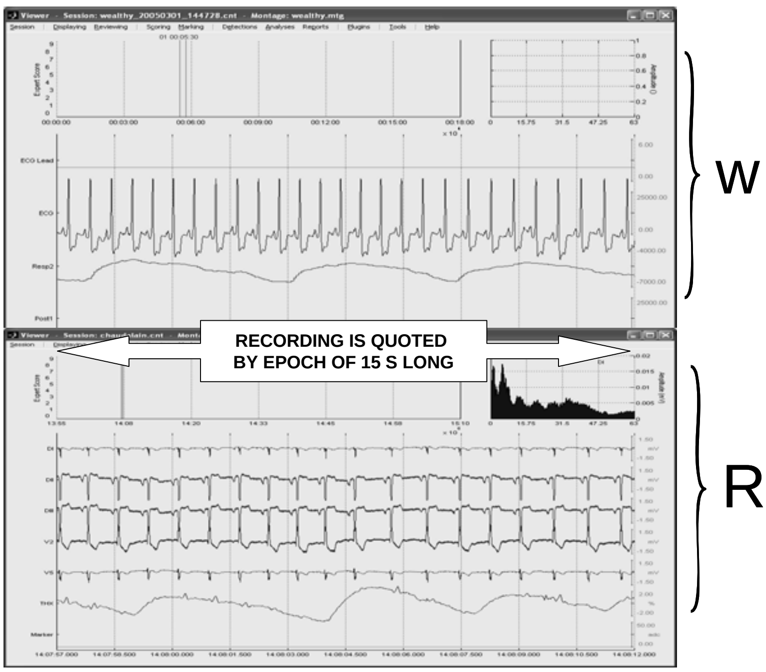

Fig. 3 Signal was displayed using the PRANA package then split in 15-sec long period (“epoch”) quoted separately from non interpretable (1) to good (4). The figure displays Wealthy signal (ECG, 1 lead, and respiratory trace) on the upper panel (“W”) and Reference signal (ECG on five leads and respiratory trace) on the lower panel (“R”).

Results

A total of 5147 epochs (21h 26min 45 sec) were analysed. Both R and W signals were rated the same level of quality 76.8 ± 3.2 % of time for ECG and 80.2 ± 1 % of time for RESP signal.

When the R signals were rated good (level 4) the W signal was rated acceptable or good (3 and 4 for ECG and 2 and 4 for RESP) 87.8 % of time for the ECG signal and 92.2 % of time for the RESP signal. Moreover, The R signal was considered better than the W signal 18.2 ± 5.2 % of time for the ECG signal and 13.1 ± 1.9 of time for the RESP signal and the W signal was considered better than the R signal 5.8 ± 1.0 % of time for the ECG signal and 8.2 ± 1.0 % of time for the RESP signal. Results from specific type of test are presented in the table 1.

Tests		**Index**			
type	Nb epochs	I.: same level of quality	II.: W good or acceptable when R is good	III.: R better than W	IV.: W better than R
		ECG signal			
CH (hot)	482	62.7 ± 7.8	86.7	20.7 ± 5.4	16.5 ± 3.4
CN (lab)	1361	76.9 ± 2.8	88.9	16.3 ± 1.8	6.4 ± 1.5
NS (night)	3304	77.6 ± 3.3	87.6	18.6 ± 3.0	4.0 ± 1.0
		RESP signal			
CH (hot)	482	70.5 ± 3.2	88.5	14.3 ± 4.9	15.2 ± 2.6
CN (lab)	1361	79.3 ± 2.6	90.4	16.8 ± 3.2	4.1 ± 2.0
NS (night)	3304	79.9 ± 1.0	93.3	11.5 ± 1.1	8.7 ± 1.0
All results are in % of recording time					

Table 1 : results for each type of test :

- CH (hot) is a mix of resting and exercising period in hot and wet environment
- CN is a mix of light lab activity and rest in neutral conditions
- NS (night) is the signal form a normal night.

The index are :

- I. same level of quality : the percent time of the recording time during with both systems R and W give the same quality of signal
- II. the percent time of the recording during which the W signal is rated as 3 or 4 for ECG and 2 or 4 for RESP when the R signal is rated 4
- III. And IV.: percent of recording time where one signal is better (whatever the difference) than the other one.

Discussion

In controlled setting (CH and CN) the partial anatomical overlapping between the electrodes of the two systems was carefully monitored and minimized during the preparation phase, while this problem cannot be totally avoided during natural setting (NS).

As described in previous papers, Wealthy shirt requires the use of hydrogel membranes to improve skin-electrode contact and to reduce the electrical impedance. There was no reported problems due to discomfort related to hydrogel membrane whatever the length of the recording. Moreover, CH tests were performed without using the hydrogel membrane; both ECG and RESP W signals improve during the test while it was going worse for the R ones. As a consequence, the general concordance between signals is the lowest during this test (table 1, index I) and W signal is more often better than R signal than in other tests (table1, index IV). This effect was probably due to the sweat heavily produced during the test (Fig. 4) which tends to improve electrical impedance between the skin and the WEALTHY electrodes while it tends to unstuck tapped electrodes used for the Reference signal.

All subjects referred Wealthy shirt was comfortable.

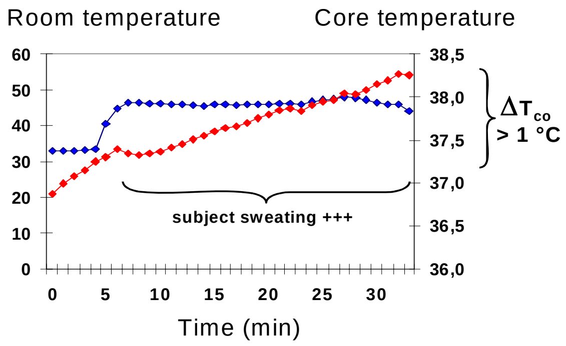

Fig. 4 During a CH (hot) test the subject's core temperature (red diamond) goes up during hot exposure (blue diamond). During this period, the subject is sweating heavily.

Conclusions

From the results reported in table 1, the following conclusion can be summarized:

1. In healthy subjects, WEALTHY gave a signal as good as, or even better than, the reference system, in 82.6 ± 4.1 % of time for ECG and 88.4 ± 1.5 % of time for RESP.
2. This proportion goes up significantly when the subject is sweating. After several minutes of heavy sweating, the signal from WEALTHY is regularly better than the reference signal.
3. Analysis was made on no-treated signals and the feeling of the evaluator is that the general performance of the Wealthy system could be greatly enhanced by a following post-processing

A significant improvement of the signal was observed between a first and a second version of the WEALTHY jacket; finally the customisation of the shirt to the subject/patient has greatly improved the signal. There is therefore no more need for the same kind of evaluation but rather for field of application specifically designed.

From WEALTHY to PROETEX

From the experience gained during Wealthy project, a new project aiming at emergency operators monitoring has raisen. PROETEX (IST-4-026987, started in February 2006, still in progress) is an IP with the goal to build a textile platform where all the monitoring, communication and power management devices are integrated into fully functional wearable and can directly communicate with each other and with ambient planning and management systems.

The goal of the project is to improve the safety and efficiency of emergency workers by empowering them with wearable sensing and transmission systems that monitor their health, activity, position and their environment during such risky situations.

In the frame of this project several prototypes with different functionalities will be developed [5]:

– Inner Garment
    - Heart rate
    - Breathing
    - Core Temperature
    - Pulse Oximetry (SpO2)

  - Dehydratation
- Outer Garment
  - GPS location
  - Temperature of the environment (air)
  - Motion sensor (posture and activity)
  - Heat flux (fire fighter garment only)
- Patch for Victim
  - Heart rate
  - Breathing
  - Core Temperature
  - Pulse Oximetry (SpO2)
  - Blood pressure
  - CO saturation
- Shoes
  - Exochemical sensors

An example of the prototypes realized by Smartex for Proetex inner garment is showed in the

Fig. 5.

Fig. 5 Proetex Inner Garment

This prototype is able to monitor an ECG lead, core temperature and respiratory activity. The prototype is under study, to evaluate the performance in the real scenario and to design the second version according tests results. The system has been characterized first at laboratory level; all the functionalities have been tested.

For instance in Fig. 6 is shown the comparison between the HR acquired with the new portable electronics developed in Proetex project and Wealthy PPU, this test has been done to evaluate the efficiency of heart rate algorithm in the real context of use.

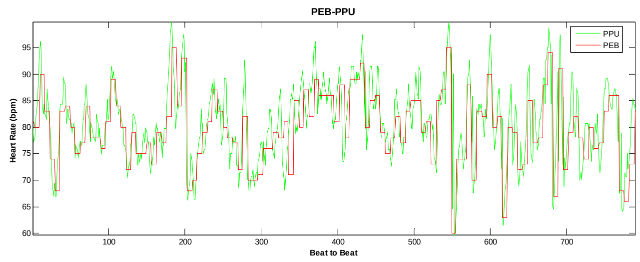

Fig. 6: Comparison between the HR signal extrapolate with PEP and PPU devices.

The differences in the waveform are due to the different approaches in the heart rate estimation: the PPU calculates the instantaneous heart rate, whereas the PEP updates a new heart rate value approximately every 4 seconds (this estimation is based on the last four beats).

Summary

The systems presented in this paper allow continuous and remote monitoring of operators requiring safety and security advices otherwise available only in a controlled environment. This is achieved by means of wearable sensors, portable data acquisition and transmission devices connected to the sensors, wireless telecommunications and monitoring software installed in a centralized processing site. Results from validation study presented in this paper enable remote health monitoring addressing different scenarios of use. The potentiality of this approach is clearly documented by the tests done; the natural evolution of these system has been sketched, leading to new customized systems addressing emergency applications.

Acknowledgments

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