

Working Garment Integrating Sensor Applications Developed Within the PROeTEX Project for Firefighters

Guy Voirin

Abstract In the frame of the European project PROETEX, CSEM continued to develop applications in the field of smart garment for monitoring vital signs and environment of the wearer. This European integrated project grouped 23 partners from all over Europe. The objectives of the project were to develop smart garments for firefighters and rescuers that will help them and their headquarters to know the location, the capacity, and the encountered risks of emergency personnel on the intervention's field. The smartness was given by the network of integrated sensors and the communication capacities of the developed garments. The inner garments integrated life sign monitoring sensors for heart rate (HR), respiration rate, body temperature, etc. The outer garments were equipped with sensors to determine environmental risks (chemical, temperature), the situation of the rescuer (activity, attitude, localization), and the control system with a communication module. The system was tested in the laboratory and the intervention's field. In the laboratory, it was compared with reference measurement systems and proved its functionality. Then it was tested with firefighters and rescuers in training situations with exercises of real rescue and fire operations. It proved its ability to provide relevant information to the management of emergency personnel during operation. Integration of sensors in garments is an emerging technology that will find applications not only for monitoring people in extreme situations but also for monitoring people during sport training or for monitoring patients and elderly people at home.

Keywords Wearable systems • Smart garment • Protection • Monitoring

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1 Introduction

CSEM has been active in the field of on-body monitoring for more than 10 years. Expertise has been acquired on physiological monitoring and parameters like electrocardiogram (ECG), heart rate (HR), peripheral capillary oxygen saturation (SpO_2), and skin temperature (ST). More recently, in the frame of the European project BIOTEX, CSEM acquired expertise on sensing microsystems for parameters in body fluids like sweat or wound exudate [1].

The ambitious strategy for sensors' development and integration in textiles (Fig. 1) was to first develop physiological sensors and biosensors for on-body applications and then to integrate them in wearable garments for seamless monitoring of patients, athletes, or workers exposed to extreme conditions, such as firefighters.

The European project PROeTEX is one pillar of this strategy and deals with smart garments to monitor firefighters and their environment during fire interventions. Smart garments in this context means garments integrating a network of sensors, microprocessors, energy sources, and communication tools.

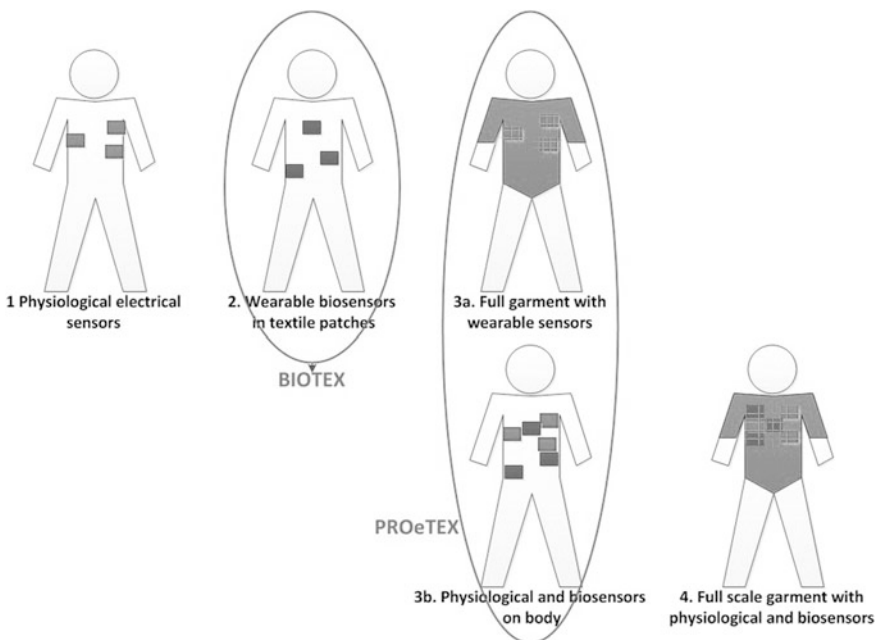


Fig. 1 Strategy for sensor integration in garments (from <http://csnej106.csem.ch/sfit/default.htm>)

2 General Concept of the PROeTEX Project

2.1 Background

Rescuers and firefighters are professionals that work in difficult conditions. They may be led to put in danger their life for others. In these situations, their judgement can be affected by stress due to physical efforts or temperature. Therefore, it is key for the operation headquarters to know and evaluate the situation in which fire-fighters are engaged, in order to take decisions about the operation's execution. There is a need to determine with accuracy the location, the environmental conditions, and the professionals' ability on the frontline.

In light of the latest developments in wireless communication and the inter-connections between the different systems, it has been possible to envisage a development of a system (Fig. 2) with the following capabilities [2]:

- Provide information about the personnel involved on the intervention's field and about their activities.
- Ensure that the entire personnel are monitored to determine whether they become incapacitated and, if this occurs, rapidly set up an extraction plan from the operation's field.
- Use physiological and biological sensors to predict the capacity of engaged personnel to operate by monitoring their level of physical and psychological stress.
- Determine the environmental, thermal, chemical (toxic gases, chemical agents, corrosive vapors) and physical risks (falls, crushes, blasts).



Fig. 2 PROeTEX concept

- Store an individual event log per user for preventive medicine and epidemiological studies.
- Monitor the state of health and location of injured civilians in order to maintain an overall plan of evacuation based on constantly updated relevant information.

These capabilities are particularly important in major, large-scale events such as forest fires, earthquakes, or major terrorist incidents, where large numbers of emergency personnel are working for extended periods of time over large areas and where significant numbers of injured civilians are involved.

2.2 Concept

In order to bring a solution to the rescuers' and firefighters' problems, a European consortium was set up. It comprised more than 20 groups from universities, research centers and companies. The basic concept put forward in the project is to have an inner garment directly on the body with sensors for life signs monitoring, an outer garment with sensors for activity, location, and environmental sensing, and a communication unit that will perform local on-body communications and make the interface with a system with a longer range to be able to connect with the system in use during the operation. The solution also offers a system for life signs monitoring of victims to help rescuers to classify the victims depending on the seriousness of their injuries and the risk for their life and to be able to intervene in case their conditions worsen. One part of the project was dedicated to long-term R&D for the development of fiber-based micro- and nanosystems to prepare the miniaturised sensors to be integrated in the textile of the future.

3 The Smart Garments Developed in the PROeTEX Project

The inner garment developed in the PROeTEX project consisted of a shirt integrating textile electrodes for ECG measurement and respiration measurement by plethysmography, a piezoresistive textile patch for respiration measurement (measurement of the expansion of the chest during respiration), and a temperature sensor for ST measurement and core temperature estimation. The T-shirt can be completed by peripheral capillary oxygen saturation (SpO_2) sensors and a biological sensor for the measurement of sodium content in sweat for dehydration estimation. The SpO_2 sensor is composed of LEDs and photodiodes. The different signals are processed in order to extract the best signal and to reduce artifacts created by the different movements of the body. The SpO_2 sensor is integrated in the form of a large "electrode" with integrated electronics. The elastic garment maintains the "electrode"

in contact with the skin. It is an alternative to electrodes and textile being directly incorporated into the fabric.

The outer garment is composed of the main electronic system, which is the base of the body network. This network links different sensors together: a GPS module for position determination in outdoor situations, several three axis accelerometers for activity and posture determination, the sensors for monitoring the environment of the firefighters including a temperature sensor, a heat flux sensor, and a gas sensor. This wired sensor network is extended to sensors in the boot using a ZigBee-like wireless module. The network is linked with a Bluetooth communication module to the long-distance communication module (Wi-Fi) via a textile antenna. The network also includes alarms that can be activated by the system to alert the firefighters when a specific dangerous situation is detected. The alarms are acoustic and optical, a buzzer and high-power flashing LED lights, respectively. The system also has energy sources; two types were used: a flexible prototype developed at CEA (France) for direct integration into the garment and a commercial Li-ion battery pack (Fig. 3).

The electronic system was integrated into the garment in different pockets and by guide wires sewn into garments. Several releases of the system were manufactured and tested.

4 The Tests of the Firefighter Garments

Two different types of tests were made with the system. Laboratory testing was conducted to verify the functionality of the system and to verify the accuracy of the different sensors using gold standard devices for comparison.

The ergonomics of the system were tested with the firefighter and the rescuer team. The goal of these tests was to show that the system would not be a disruptive factor due to the size of some of the electronic devices. The system was easily accepted by the firefighters because their usual outer garment is already quite heavy and the use of electronic devices does not make the situation worse. Moreover, during the interventions, firefighters often wear respiratory equipment, which is by far more cumbersome.

After the laboratory tests, the system was tested and demonstrated in exercises simulating real situations. The exercises were done in a test location for firefighters and rescuers in Italy. Different exercises were performed by firefighters and rescuers like extinction of fire, carrying victims, or smoke divers' training. Figure 4 presents several pictures taken during these exercises.

The signals of the different sensors were recorded using the system, sent using the wireless communication element, and displayed on the computer representing the headquarters of the operations (Fig. 5).

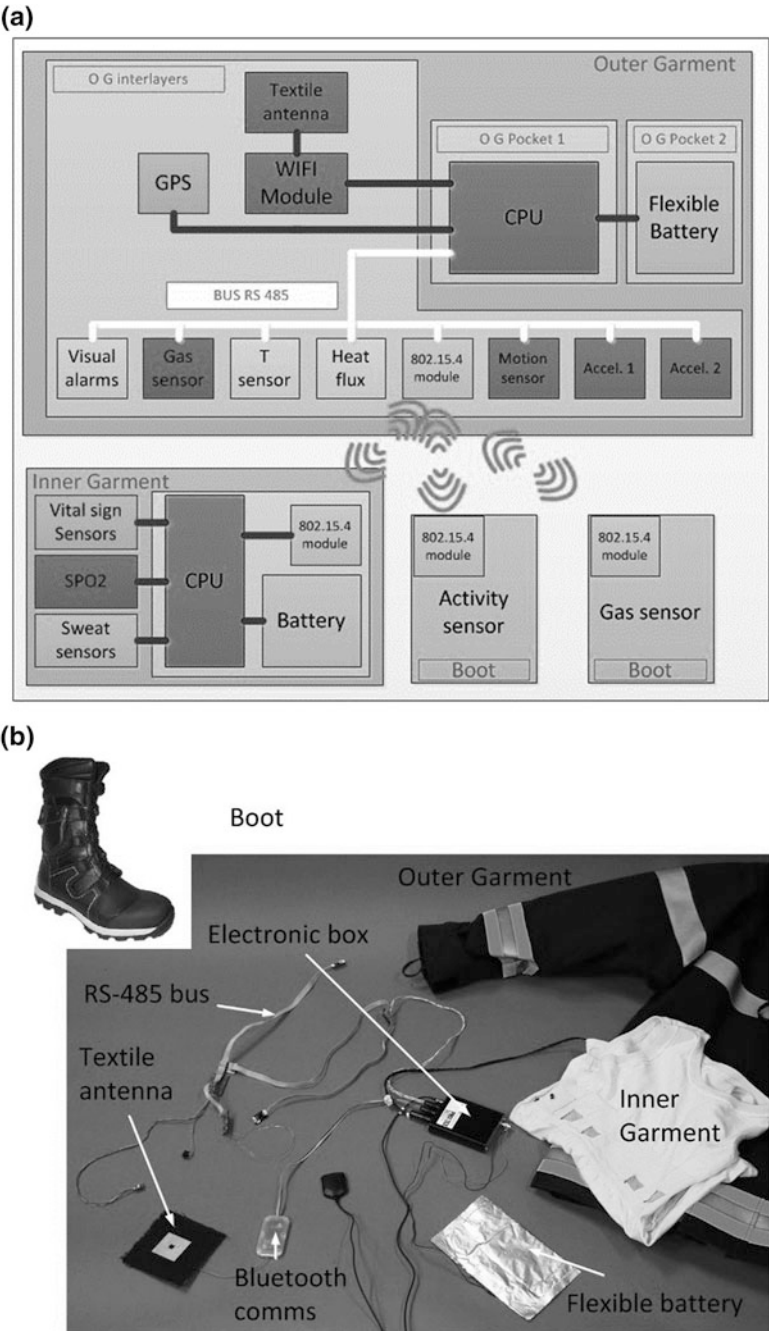


Fig. 3 **a** Block diagram of the electronic system. **b** View of a first release of the garment prototype with the sensor network

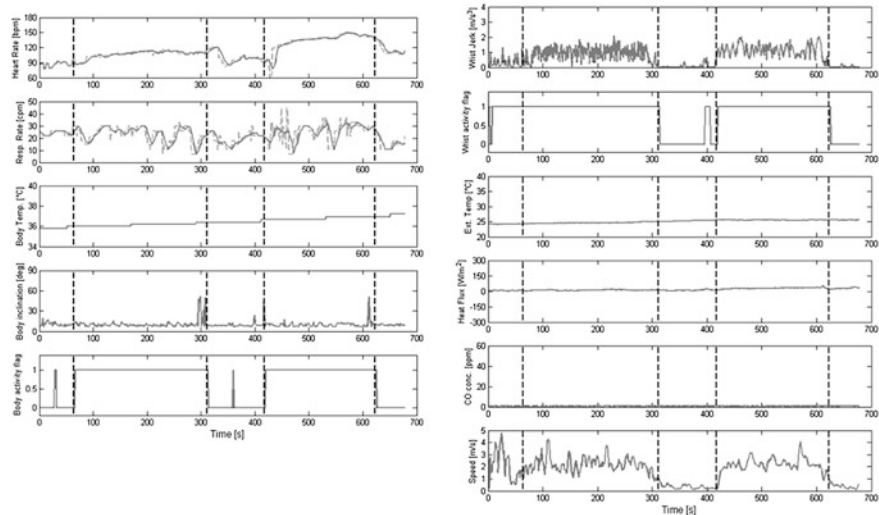


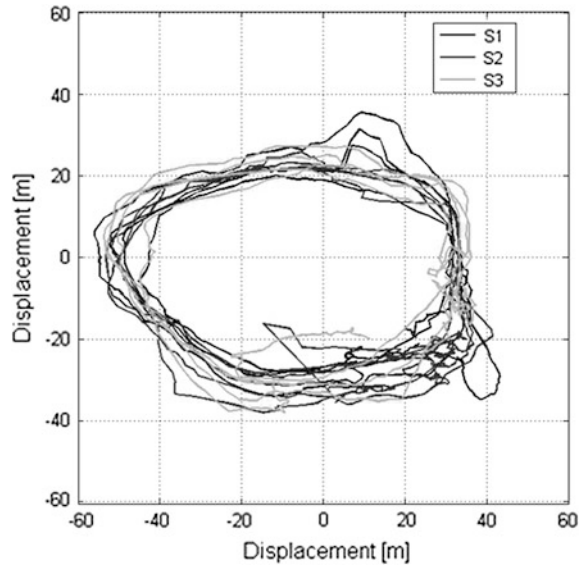
Fig. 4 Pictures of firefighters during exercises simulating operation in the field



Fig. 5 Display of the signals of the different sensors on the computer representing the headquarters of the operation

The location of firefighters or rescuers is done using GPS; this works well outdoors, but it is not adapted to firefighter operations inside buildings. The position is acquired with the wearable electronic device and sent to the supervising computer where the data can be displayed either as x, y coordinate (Fig. 6) or superimposed on a map or satellite picture in a localization software.

Fig. 6 Trace of the x, y position of three firefighters during an exercise of portage



The system's features are summarized in the following table:

- Inner garment:
 - HR (ECG): 50–240 bpm
 - Respiration rate: 5–60 bpm
 - Skin temperature: at 30 °C, accuracy ± 0.33 °C; in the range 10–50 °C, ± 0.5 °C
 - Na⁺ concentration in sweat
 - SpO₂: 70–100 %, resolution 1 %, accuracy ± 3 %
- Outer garment:
 - Localization: GPS
 - External temperature: –70 °C, 500 °C; heat flux
 - Two 3 axis accelerometers for movement and posture determination
 - Environmental gas sensing: CO, CO₂
 - Alarms: visual, acoustic

5 Outlook and Conclusion

Within the PROeTEX project, new ways of integrating sensors in textiles were tested. Different sensors with fiber geometry were tested like organic transistors, organic LED, and biosensing optical fibers. In view of the integration of wearable sensors into textiles, the fiber geometry offers an attractive support for sensors as they can be woven like standard yarn, to some extent, and offer minimally invasive, on-body,

highly sensitive measurements of health monitoring. At CSEM, biosensing optical fibers were developed; they consist of optical fibers with a sensing layer comprising the chemical or biological sensing element, a light source, and a detector (photodetector, spectrometer). Multiple reflections of the light propagating in the optical fiber allow sensing of optical changes in the proximity of the fiber core—within the evanescent field. Therefore, the sensitive layer is placed directly on the core of the optical fiber, replacing the original cladding that confines light in the core of commercial glass or polymer fibers. Sensing optical fibers have been designed for performing pH measurements of sweat by incorporating a pH-sensitive dye in the sensitive layer deposited on the fiber core. For the detection of bioanalytes such as lactate or glucose, work has started for the development of sensitive layers incorporating specific enzymes (e.g., lactate or glucose oxidase). These sensitive fibers are promising for the sensing of biological parameters on body as they will give more information about stress, tiredness, or dehydration of the firefighters.

In the PROeTEX project, garments were developed to help workers to have a better knowledge of their environment and their capacities and to receive information through simple acoustic or optical alarms. The next step for “smart garments” will be to have a direct action in the worker environment, for example, in the project prosys laser [3], where development was dedicated to the protection of workers using a handheld high-power laser processing system, by using active functional multilayer textiles incorporating sensors that detect laser exposure. By means of a safety control unit (the smartness of the garment), the protective cloth is able to deactivate the laser beam automatically for the safety of the worker.

The PROeTEX project has shown that it is possible to develop garments that integrate numerous sensors that can monitor parameters of the environment and of the biophysiological state of the workers in extreme conditions. In the future, the “smart garment” will have more and more interaction with the users and will even modify their environment for their safety. PROeTEX has also demonstrated that the development of wearable sensors can follow two ways, either as an electronic component integrated into textiles or as sensitive fibers directly integrated into the textile fabrics. The PROeTEX developments are the premises of applications that will not be reserved to firefighters and rescuers but will also find applications in the field of sport training and medical devices.

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