A Modular BLE-Based Body Area Network Embedded into a Smart Garment for Rescuers Real-Time Monitoring in Emergency Scenarios

Giulia Sedda*[a], Giulia Baldazzi[b], Salvatore Spanu[c], Antonello Mascia[d], Andrea Spanu[e], Piero Cosseddu[f], Annalisa Bonfiglio[g] and Danilo Pani[h]

Department of Electrical and Electronic Engineering (DIEE), University of Cagliari, Cagliari, Italy

Keywords: Body Area Network, BLE, First Responders, Wearable Sensors, Smart Garment.

Abstract: In this work, we present a prototype of a smart technical underwear for first responders involved in search-and-rescue operations, to be worn under the rescuer's professional uniform. Polymer-based electrodes able to detect ECG and EMG signals, and organic transistor for joint angles estimation are embedded into the smart garment. The technical underwear implements a body sensor network of BLE nodes able to acquire, process in real-time and transmit electrophysiological and biomechanical data from the sensors to a custom Android app on the rescuer's smartphone. The app geolocates the data by using the information of the GPS integrated into the smartphone and sends them to the control center for remote monitoring. The system features high modularity, as the rescuer can adopt a subset of sensors depending on the specific operative context, without any app configuration.

1 INTRODUCTION

First responders involved in difficult search-and-rescue operations are subject to hazardous conditions, and it is critical to take care of their safety and health status during the operations. The development of smart garments with physiological and biomechanical sensing capabilities, to be integrated in a broader monitoring system, is then of paramount importance for their safety. In this context, wearable technologies for vital signs monitoring represent a great opportunity to obtain unobtrusive sensing allowing free movement and operation.

Recently, various sensorized technical clothing for rescuers have been designed, such as the system developed in the ProeTEX (Protection e-Textiles: Micro-Nano-Structured fiber systems for Emergency-Disaster Wear) European project, which integrates wearable and portable sensors, in order to detect both parameters representing the health status of the firefighter and environmental variables (Curone et al. 2010). The sensing nodes, both custom and commercial, devoted to assessing the health status of the emergency operator, are distributed in an internal garment and provide the heart rate, the breathing rate, the body temperature and the blood oxygen saturation. An outer garment assesses the operator activity state and monitors the surrounding environment, by estimating the operator position, activity, and posture, and measuring the external temperature, the presence of toxic gases, and the heat flux passing through the garments. The internal garment is a T-shirt directly in contact with the user skin; to maximize the user comfort, textile-based and/or textile-compatible technologies have been employed. Both sensors and electrodes are connected to the electronic modules through textile-conductive cables integrated in the shirt. All the data are transmitted remotely to the operation manager in real-time through the Wi-Fi network.

In 2014, Salim et al. designed a sensorized T-shirt to monitor physiological parameters such as skin

[a] https://orcid.org/0000-0002-9662-7697
[b] https://orcid.org/0000-0003-1275-4961
[c] https://orcid.org/0000-0002-2600-8241
[d] https://orcid.org/0000-0002-4185-7225
[e] https://orcid.org/0000-0003-0331-7516
[f] https://orcid.org/0000-0003-4896-504X
[g] https://orcid.org/0000-0001-7866-4526
[h] https://orcid.org/0000-0003-1924-0875

Sedda, G., Baldazzi, G., Spanu, S., Mascia, A., Spanu, A., Cosseddu, P., Bonfiglio, A. and Pani, D.
A Modular BLE-Based Body Area Network Embedded into a Smart Garment for Rescuers Real-Time Monitoring in Emergency Scenarios.
DOI: 10.5220/0011778100003414
In *Proceedings of the 16th International Joint Conference on Biomedical Engineering Systems and Technologies (BIOSTEC 2023) - Volume 1: BIODEVICES*, pages 177-181
ISBN: 978-989-758-631-6; ISSN: 2184-4305

temperature, heart rate, heat flux, and ultraviolet exposure, in order to assess the firefighter's thermal status and alert workers regarding the heat exhaustion while operating in hot industrial environments. Sensor data and alerts are sent wirelessly (XBee series-1 radio) in real-time to the wearer, by using a phone App, and to the remote center.

Afterwards, a smart T-shirt made out of Nomex fabrics, which has inherent flame-resistant and very low heat-conductance properties, was designed to detect the mental stress of the firefighters. The smart garment monitors their physiological signals (i.e., the heart rate) and the environmental conditions (temperature and humidity) and processes this information with a machine learning algorithm (Sandulescu et al. 2015). The system also integrates movement sensors and a microphone for team communication, whose features are elaborated for stress monitoring of rescuers. Wires connecting to the data acquisition and processing unit are woven in the garment. Data are sent remotely in real-time by using the ZigBee protocol.

As part of the H2020 Search & Rescue European Project (https://search-and-re-rescue.eu/), we designed, developed, and tested on the field a smart underwear implementing a BLE-based modular wearable system for rescuers operating in critical emergency contexts, such as searching people trapped under the rubble. The system is able to collect physiological and biomechanical parameters measured by custom-designed wireless sensing nodes acquiring data (ECG, EMG, and strain) from as many sensors embedded in the smart underwear. Each node sends the edge-processed data to a wearable hub, represented by a smartphone, which is in charge of local visualization and real-time transmission to the operational control center.

2 SYSTEM ARCHITECTURE

The developed smart underwear has been designed to be worn under the rescuer’s uniform, allowing monitoring the ECG, EMG, and knee joint angle of the first responder during the search and rescue operations. It is composed of a T-shirt and leggings made of a highly breathable, stretchable, resistant, and comfortable polyester fabric.

2.1 Sensing Elements

As shown in Figure 1, the garments are functionalized in the targeted areas using a biocompatible conductive ink based on poly(3,4-ethylenedioxythiophene) polystyrene sulfonate (PEDOT:PSS) (Tsukada et al. 2012, Tseghai et al. 2020), to form electrodes able to detect cardiac and muscle biopotentials (Guo et al. 2016, Sinha et al. 2017, Pani et al. 2018, Achilli et al. 2018, Spanu et al. 2021). Two ECG electrodes are positioned on the chest, symmetrically with respect to the sagittal line, to detect the ECG according to the lead I direction. A further electrode on the back, approximately at the same height, provides the signal ground for this recording (Figure 1 - light blue circles - and Figure 2A). Experimentally, after carrying out several tests, this configuration of the electrodes proved to be the best for guaranteeing adhesion of the electrode and the acquisition of a good signal (data not shown). A couple of EMG electrodes is placed on the upper leg, to detect the activity of the vastus medialis, with a ground electrode over the knee (Figure 1 - red circles – and Figure 2A, 2D). A second couple of EMG electrodes is positioned on the gastrocnemius medialis, with the ground electrode over the shinbone. Similar to ECG, various possibilities were tested for the configuration of the electrodes for EMG, and the one chosen proved to be the best. All the electrodes were patterned directly on the finished garment using a customized screen-printing technique, as already reported in Spanu et al. (2021). The employed technique allowed to obtain perfectly functional electrodes even upon a sustained stretch of the garment.

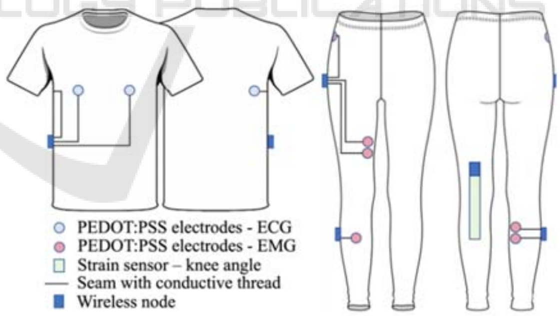

Figure 1: Overview of the smart underwear.

Biopotentials from the electrodes are read by custom-developed, low-power, low-cost, small wireless nodes (Figure 1, blue rectangles). In particular, the nodes embed the TI’s ADS1292 module, a 24-bit, 2-channel ADC with an integrated analog front-end for electrophysiological signals (ECG, EMG). The connection between the wireless node and the electrodes is made up of conductive steel threads sewn directly on the underwear (see both Figure 1 and Figures 2A, 2D). As the performance of the electrodes depends on their coupling with the skin, which must be stable and characterized by low impedance, the electrodes were firmly attached on the skin by using elastic bands able to guarantee a uniform and constant pressure over the skin (Figure 2D).

Lastly, an organic semiconductor-based strain sensor is placed over the popliteal fossa (Figure 1, the green vertical strip), that is able to dynamically change its resistance according to the angular extension of the joint (Taroni et al. 2018, Sezen-Edmonds et al. 2019). It is a three-terminal device, namely thin-film transistors (TFT), whose sensitivity can be tuned and amplified by means of the gate field, and that can be incorporated into cotton garments for measuring joint movements (Lai et al. 2019). In this case, the wireless node is directly attached to the sensors without any conductive yarn.

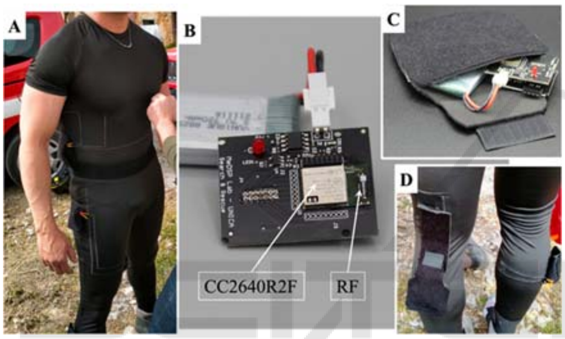

Figure 2: A: Front view of the smart underwear, with ECG and EMG electrodes for vastus medialis muscle; B: Custom-developed wireless node; C: Neoprene pocket housing the electronic node. Velcro stripes allow the pocket to be easily attached to the garment. D: Back view of the smart underwear, with detail on both the strain sensor on the left, and EMG electrodes for gastrocnemius medialis on the right.

2.2 Wireless Nodes

The wireless nodes support both acquisition and basic edge-processing features, and are housed in small neoprene pockets along with their battery, as shown in Figure 2C. They are based on a Texas Instrument CC2640R2F microcontroller, integrated in a convenient system-on-module (Figure 2B). This wireless microcontroller features an ARM Cortex-M3 processor (32 bit), running at 48 MHz, with 275 kB of non-volatile memory, ultra-low power sensor controller, and several peripheral modules (e.g. general-purpose timer modules, 12-bit ADC, UART, I2C, I2S, SSI, Real-Time Clock, and others). In particular, the ultra-low power sensor controller can interface with external sensors and collect analogue and digital data independently, while the rest of the system is in sleep mode. Lithium-polymer batteries (720 mAh, 3.7V) have been selected by overestimating the duration of the typical emergency interventions, as they can provide supply for a week at full strength. The estimated power consumption of the wireless node is about 15mW.

The CC2640R2F is provided with a radio frequency module, implementing a 2.4 GHz transceiver compatible with Bluetooth low-energy (BLE) 5.1 and earlier low-energy specifications. It is characterized by excellent receiver sensitivity (–97 dBm for BLE), selectivity and blocking performance. This is also suitable for systems targeting compliance with worldwide radio frequency regulations, i.e., ETSI EN 300 328 (Europe), EN 300 440 Class 2 (Europe), FCC CFR47 Part 15 (US), or ARIB STD-T66 (Japan).

2.3 A BLE-Based Body Area Network

Each sensor is provided with a dedicated BLE node, to foster modularity and the possibility to equip the first responder only with the useful sensors for the given scenario, avoiding over-connected and useless smart garments that could hamper the mobility and, consequently, the field operation.

Each wireless node is able to detect a single-channel signal, which is edge-pre-processed to extract the heart rate from the ECG signal, the maximum voluntary contraction of the EMG signal, and the angular extension of the knee joint. Raw data and key features (such as the heart rate) are sent to the rescuer's smartphone in real-time, by using custom-defined GATT characteristics. Data rate is signal-dependent: as such, the ECG signal is sampled and sent at 250 Hz; the EMG signal is sampled at 250 Hz, whereas its envelope is edge-computed and sent at 50 Hz; joint angles are sampled at 10 Hz and their average value is sent at 1 Hz. A custom Android app was designed to collect the data from the different wireless nodes (see Figure 3). On the smartphone, by using the information of the integrated GPS module, data are geolocated and sent to the remote web server, every five seconds in independent chunks, through Wi-Fi or cellular network.

The app is able to interact with Apache Kafka, a broker for streaming processing based on a distributed data storage, which receives the data in JSON format in real-time every 5 s. Depending on the sensor type, the data file comprises different fields; the size of the field that contains the signal depends on the sampling frequency of the data.

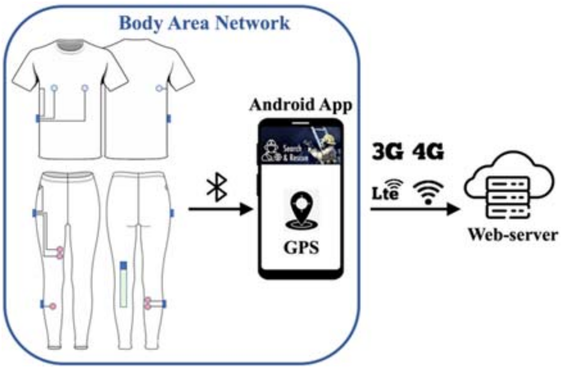

Figure 3: Overview of the system architecture.

The application has a very simple interface (Figure 4), which provides information on the sensors connected to the application, and therefore in use. In addition, the app allows real-time display of some characteristics of the Global Navigation Satellite Systems (GNSS) location, including latitude, longitude and altitude coordinates, detected through the GPS sensor embedded in the smartphone. Finally, it shows the status of communication with the server (SERVER RESPONSE: OK/NO NETWORK), and the total number of packets sent and queued (therefore not yet consumed by the server) for each of the connected nodes.

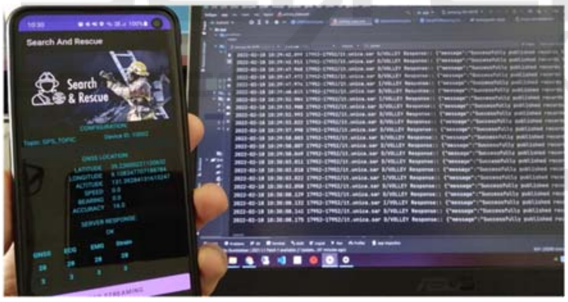

Figure 4: The Search & Rescue Android App sends the data to the web server in real-time.

3 DISCUSSION

The smart underwear prototype presented in this work differs from similar solutions described in the literature for several aspects. In fact, it consists of both a T-shirt and a leggings, compared to Curone et al. 2010, Salim et al. 2014, Sandulescu et al. 2015, allowing for monitoring the muscle contraction at the level of the lower limb and the angle of the knee joint, which give indications on the rescuer's activity.

Furthermore, the application of organic semiconductor sensors, such as electrodes for electrophysiological measurements and the strain sensor for detecting knee angle, is completely new in the search and rescue field, where it can be widely used for monitoring the physical and health conditions of the first responder in a totally non-invasive way, with innovative and low-cost materials and through technologies that have shown good performance compared to the gold standard.

In addition, the position of the nodes on the underwear is independent of that of the actual sensors, therefore it can easily be modified to meet the specific needs of the rescuer.

Another important aspect concerns the size of the node, which is miniaturized and with low power consumption compared to the solutions found in the literature: for example, for the same battery capacity (1200 mAh), each node of our prototype can work continuously for days (up to a week) with all the sensors connected, while the smart solution proposed by Salim et al. 2014 can work continuously up to 5 hours without the GPS connected.

4 CONCLUSIONS

At present, the smart underwear was successfully tested in the first two demonstrative use cases on the field envisaged in the project.

Currently, up to four sensors can be present on the underwear to sense and transmit the physiological and biomechanical data of the rescuer. The functionalities of both the smart underwear and the custom Android app are being extended to include the acquisition of signals coming from other types of sensors, also eventually integrated in the external uniform.

ACKNOWLEDGEMENTS

The authors acknowledge funding from the European Union’s Horizon 2020 research and innovation programme under grant agreement No. 882897–Search&Rescue project.

REFERENCES

Achilli, A., Bonfiglio, A. and Pani, D. (2018). Design and characterization of screen-printed textile electrodes for ECG monitoring, IEEE Sensors Journal, vol. 18, no. 10, 2018. DOI: 10.1109/JSEN.2018.2819202.

Curone, D. et al. (2010). Smart garments for emergency operators: The ProeTEX project, IEEE Transactions on

Information Technology in Biomedicine, vol. 14, no. 3. DOI: 10.1109/TITB.2010.2045003.

Guo, Y., et al. (2016). PEDOT:PSS 'wires' Printed on Textile for Wearable Electronics, ACS Applied Materials and Interfaces, vol. 8, no. 40, doi: 10.1021/acsami.6b08036.

Lai, S., Garufi, A., Madeddu, F., Angius, G., Bonfiglio, A., and Cosseddu, P. (2019). A Wearable Platform for Monitoring Wrist Flexion and Extension in Biomedical Applications Using Organic Transistor-Based Strain Sensors, IEEE Sensors Journal, vol. 19, no. 15, doi: 10.1109/JSEN.2019.2909174.

Pani, D., Achilli, A., & Bonfiglio, A. (2018). Survey on textile electrode technologies for electrocardiographic (ECG) monitoring, from metal wires to polymers. Advanced Materials Technologies, 3(10), 1800008. https://doi.org/10.1002/admt.201800008.

Salim, F., Prohasky, D., Belbasis, A., Houshyar, S., & Fuss, F. K. (2014, September). Design and evaluation of smart wearable undergarment for monitoring physiological extremes in firefighting. In Proceedings of the 2014 ACM International Symposium on Wearable Computers: Adjunct Program (pp. 249-254). DOI:10.1145/2641248.2666716.

Sandulescu, V., & Dobrescu, R. Wearable system for stress monitoring of firefighters in special missions. In 2015 E-Health and Bioengineering Conference (EHB) (pp. 1-4). IEEE. DOI:10.1109/EHB.2015.7391578.

Sezen-Edmonds, M., Yeh, Y. W., Yao, N., and Loo, Y. L. (2019). Humidity and Strain Rate Determine the Extent of Phase Shift in the Piezoresistive Response of PEDOT:PSS, ACS Applied Materials and Interfaces, vol. 11, no. 18, doi: 10.1021/acsami.9b00817.

Sinha, S. K. et al. (2017). Screen-Printed PEDOT:PSS Electrodes on Commercial Finished Textiles for Electrocardiography, ACS Applied Materials and Interfaces, vol. 9, no. 43, 2017, doi: 10.1021/acsami.7b09954.

Spanu A, Botter A, Zedda A, Cerone GL, Bonfiglio A, Pani D. Dynamic Surface Electromyography Using Stretchable Screen-Printed Textile Electrodes. IEEE Trans Neural Syst Rehabil Eng. 2021;29:1661-1668. doi: 10.1109/TNSRE.2021.3104972.

Taroni, P. J., et al. (2018). Toward Stretchable Self-Powered Sensors Based on the Thermoelectric Response of PEDOT:PSS/Polyurethane Blends, Advanced Functional Materials, vol. 28, no. 15, doi: 10.1002/adfm.201704285.

Tseghai, G. B., Mengistie, D. A., Malengier, B., Fante, K. A., and Van Langenhove, L. (2020). PEDOT:PSS-based conductive textiles and their applications, Sensors (Switzerland), vol. 20, no. 7. doi: 10.3390/s 20071881.

Tsukada, S., Nakashima, H., and Torimitsu, K. (2012). Conductive polymer combined silk fiber bundle for bioelectrical signal recording, PLoS ONE, vol. 7, no. 4, doi: 10.1371/journal.pone.0033689.